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SUMMARY TECHNICAL REPORT
OF THE
NATIONAL DEFENSE RESEARCH COMMITTEE

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SUMMARY TECHNICAL REPORT OF DIVISION 14, NDRC

VOLUME 1

RADAR: SUMMARY REPORT AND HARP PROJECT

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DIVISION 14
A. L. LOOMIS, CHIEF

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WASHINGTON, D. C., 1946

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NOTES ON THE ORGANIZATION OF NDRC

The duties of the National Defense Research Committee were (1) to recommend to the Director of OSRD suitable projects and research programs on the instrumentalities of warfare, together with contract facilities for carrying out these projects and programs, and (2) to administer the technical and scientific work of the contracts. More specifically, NDRC functioned by initiating research projects on requests from the Army or the Navy, or on requests from an allied government transmitted through the Liaison Office of OSRD, or on its own considered initiative as a result of the experience of its members. Proposals prepared by the Division, Panel, or Committee for research contracts for performance of the work involved in such projects were first reviewed by NDRC, and if approved, recommended to the Director of OSRD. Upon approval of a proposal by the Director, a contract permitting maximum flexibility of scientific effort was arranged. The business aspects of the contract, including such matters as materials, clearances, vouchers, patents, priorities, legal matters, and administration of patent matters were handled by the Executive Secretary of OSRD.

Originally NDRC administered its work through five divisions, each headed by one of the NDRC members. These were:

Division A—Armor and Ordnance
Division B—Bombs, Fuels, Gases, & Chemical Problems
Division C—Communication and Transportation
Division D—Detection, Controls, and Instruments
Division E—Patents and Inventions

In a reorganization in the fall of 1942, twenty-three administrative divisions, panels, or committees were created, each with a chief selected on the basis of his outstanding work in the particular field. The NDRC members then became a reviewing and advisory group to the Director of OSRD. The final organization was as follows:

Division 1—Ballistic Research
Division 2—Effects of Impact and Explosion
Division 3—Rocket Ordnance
Division 4—Ordnance Accessories
Division 5—New Missiles
Division 6—Sub-Surface Warfare
Division 7—Fire Control
Division 8—Explosives
Division 9—Chemistry
Division 10—Absorbents and Aerosols
Division 11—Chemical Engineering
Division 12—Transportation
Division 13—Electrical Communication
Division 14—Radar
Division 15—Radio Coordination
Division 16—Optics and Camouflage
Division 17—Physics
Division 18—War Metallurgy
Division 19—Miscellaneous
Applied Mathematics Panel
Applied Psychology Panel
Committee on Propagation
Tropical Deterioration Administrative Committee

NDRC FOREWORD

As events of the years preceding 1940 revealed more and more clearly the seriousness of the world situation, many scientists in this country came to realize the need of organizing scientific research for service in a national emergency. Recommendations which they made to the White House were given careful and sympathetic attention, and as a result the National Defense Research Committee [NDRC] was formed by Executive Order of the President in the summer of 1940. The members of NDRC, appointed by the President, were instructed to supplement the work of the Army and the Navy in the development of the instrumentalities of war. A year later, upon the establishment of the Office of Scientific Research and Development [OSRD], NDRC became one of its units.

The Summary Technical Report of NDRC is a conscientious effort on the part of NDRC to summarize and evaluate its work and to present it in a useful and permanent form. It comprises some seventy volumes broken into groups corresponding to the NDRC Divisions, Panels, and Committees.

The Summary Technical Report of each Division, Panel, or Committee is an integral survey of the work of that group. The first volume of each group's report contains a summary of the report, stating the problems presented and the philosophy of attacking them, and summarizing the results of the research, development, and training activities undertaken. Some volumes may be "state of the art" treatises covering subjects to which various research groups have contributed information. Others may contain descriptions of devices developed in the laboratories. A master index of all these divisional, panel, and committee reports which together constitute the Summary Technical Report of NDRC is contained in a separate volume, which also includes the index of a microfilm record of pertinent technical laboratory reports and reference material.

Some of the NDRC-sponsored researches which had been declassified by the end of 1945 were of sufficient popular interest that it was found desirable to report them in the form of monographs, such as the series on radar by Division 14 and the monograph on sampling inspection by the Applied Mathematics Panel. Since the material treated in them is not duplicated in the Summary Technical Report of NDRC, the monographs are an important part of the story of these aspects of NDRC research.

In contrast to the information on radar, which is of widespread interest and much of which is released to the public, the research on subsurface warfare is largely classified and is of general interest to a more restricted group. As a consequence, the report of Division 6 is found almost entirely in its Summary Technical Report, which runs to over twenty volumes. The extent of the work of a Division cannot therefore be judged solely by the number of volumes devoted to it in the Summary Technical Report of NDRC: account must be taken of the monographs and available reports published elsewhere.

To A. L. Loomis, Chief of Division 14, the men who worked under his direction, and the personnel of the Division's contractors belongs major credit for the perfection of a device which forcefully altered the course of the war. The application of radar by all Services in all theaters of operation is an eloquent testimonial not only to the skill of these men but also to their will, their loyal cooperation, and their scientific integrity. The Summary Technical Report of the Division, prepared under the direction of the Division Chief and authorized by him for publication, therefore not only describes a major portion of their technical activities but is also a record of able American scientists and engineers cooperating fully in the defense of their country.

It is assuring to know that their contributions in the new field of microwaves will not be placed in intellectual cold storage to await purely military applications, but instead will soon find use in the industry, the transportation, the communications, and the scientific researches of a peacetime world.

For their work in opening a broad entrance to a new field of knowledge as well as for their invaluable contributions in a time of desperate strife, we join the Nation in expressing our sincere appreciation.

VANNEVAR BUSH, Director
Office of Scientific Research and Development

J. B. CONANT, Chairman
National Defense Research Committee

FOREWORD

Division 14 of the National Defense Research Committee was responsible for the microwave radar and Loran developments within the Office of Scientific Research and Development. Its original purpose, as defined at one of the early Division meetings, was "to organize and coordinate research, invention, design and manufacture in order to obtain the maximum number of effective applications of microwaves in the minimum time." Under this directive, Division 14 established and administered a total of 137 OSRD contracts with 18 academic and private research institutions, and 39 industrial concerns entering into almost every phase of the country's wartime radar program. The principal contract, accounting for approximately 80 per cent of the Division's contract appropriations, was to the Massachusetts Institute of Technology Radiation Laboratory. This laboratory through continuous growth and expansion of the scope of its activities became the center of microwave radar research and development effort.

The success of the program was without question due to the close collaboration of the many participating agencies and institutions. Many of the country's academic and industrial institutions worked with the Radiation Laboratory in research and development programs under Army and Navy as well as OSRD contracts. Radio and electrical equipment manufacturers were responsible for final engineering and large scale production of components and systems. The Army and Navy carried out procurement planning, proof testing, training, and the elaborate functions of supply and maintenance. Close technical liaison, furthermore, was maintained throughout World War II with radar research organizations of the British Commonwealth of Nations. The contributions of the many participating organizations must be acknowledged by any single agency attempting to present its final report.

The NDRC Summary Technical Report is intended to include the pertinent results of each Division's program. The selection of material for such a report invariably presents a difficult problem. A choice must be made from the work of many organizations and individuals during a complex five-year program.

The Division 14 Summary Technical Report consists of three volumes. The first, *Radar*, contains a summary of the Division 14 and Radiation Laboratory activities and selected project-reports, and appendices listing the Division's projects and contracts. It is intended to serve as a general guide to the Division's activities. Volume 2 of the Division 14 STR is entitled *Military Airborne Radar Systems* [MARS]. This volume is a detailed treatment of the design, development, installation, maintenance, and performance of aircraft radar for such applications as search, bombing, navigation, interception, and fire control. The volume is intended as a general text for use by officers and civilian engineers concerned with almost any aspect of aircraft radar development, engineering, procurement, training, or operational use. Volume 3 contains a complete bibliography of the contract and division reports prepared during the course of the program.

The largest publication effort of Division 14 is the *Radiation Laboratory Series* prepared by the MIT Radiation Laboratory for publication by the McGraw-Hill Book Company. This set of monographs is considered as a supplement to the Division 14 Summary Technical Report. It consists of some twenty-seven volumes and an index and is a complete report on the state of the radar art at the end of World War II, including texts on fundamental electronics, components and systems design and engineering, peacetime applications, and Loran navigation. A list of the titles and an abstract of each book is contained in Volume 3.

The progress and interim technical reports submitted by the MIT Radiation Laboratory and the other Division 14 contractors constitute valuable reference material on the division's program. They cover specific aspects of the work and are not duplicated by the Summary Technical Report or the *Radiation Laboratory Series*. All of the approximately 2,000 of these reports have been indexed by report number, subject, organization, and, in the case of the

Radiation Laboratory reports, by author in the bibliography of Volume 3. Microfilm prints of these reports are available to those who have access to the Summary Technical Reports.

Another category of reports which are included in the bibliography and microfilms are the Division 14 project reports. These were bimonthly reports of activities to the Army and Navy. Included are pertinent technical details of the systems, projects, and summaries of the basic research and component development activities. The final project report, NDRC 14-565, dated December 1945, reviews the entire program of the Division. It contains an index of all Division 14 projects, Service Projects, with cross references to contracts and Army and Navy equipment designations.

The history of Division 14 has been prepared and edited by H. E. Guerlac for publication with the other volumes of the OSRD history by the Little, Brown Company, Inc., Boston. It traces the early work on radar before the war by the Army, Navy, British, and various private institutions, describes the origin of NDRC's microwave development activities, the foundation of the Massachusetts Institute of Technology Radiation Laboratory and gives a historical summary of the principal Division systems and components resulting from the research program. A final section that should be of general interest reports on the field service activities of the Division and the operational results obtained with several types of microwave radar equipment.

This first volume of the Division 14 Summary Technical Report does not purport to review completely all Division 14 activities. Parts I and II give some of the highlights of the Division's program with comments on the administration of the Radiation Laboratory and its relation with industry and the government agencies concerned with the production and use of radar. They also tell the story of the Microwave Committee which preceded Division 14 and of the establishment and organization of the Radiation Laboratory program. The volume also contains a brief description of the principal Division 14 projects. One section is devoted to the magnetron developments of the Columbia University Radiation Laboratory. However, it has not been possible to cover more than a few major projects of the Division.

Part III, "Harp, Material with Artificially Constructed Dielectric Constant and Permeability," reports on a new material development project at the Laboratory for use in radar camouflage, identification systems, and other special applications. The article was not included in the *Radiation Laboratory Series* for security reasons.

Two important publications which were originally intended for inclusion in the Division 14 Summary Technical Report were deleted and arrangements made for their publication elsewhere. They are *Development of Cadillac Airborne Early Warning Systems*, C. J. Kelly, Field Station, Naval Research Laboratory, Boston, and *The Gun Fire-Control System, Mark 56*, Navy Publication OP-1600 E.

I should like to express my appreciation to the authors, L. A. DuBridge, H. E. Guerlac, M. H. Johnson, O. Halpern, and to the other members of the Radiation Laboratory and Division 14 staff who assisted in the preparation of this volume.

A. L. Loomis,
Chief, Division 14

TITLES OF DIVISION 14 SUMMARY TECHNICAL REPORTS

SUMMARY TECHNICAL REPORT OF DIVISION 14, NDRC

VOLUME 1 RADAR: SUMMARY REPORTS AND HARP PROJECT
VOLUME 2 MILITARY AIRBORNE RADAR SYSTEMS (MARS)
VOLUME 3 BIBLIOGRAPHY OF DIVISION 14 AND RADIATION LABORATORY REPORTS

RADIATION LABORATORY SERIES

(Published by the McGraw-Hill Book Company)

1. RADAR SYSTEM ENGINEERING, Louis N. Ridenour
2. RADAR AIDS TO NAVIGATION, J. S. Hall
3. RADAR BEACONS, A. Roberts
4. LORAN, J. A. Pierce, A. A. McKenzie, R. H. Woodward
5. PULSE GENERATORS, G. N. Glasoe, J. V. Lebacqz
6. MICROWAVE MAGNETRONS, George B. Collins
7. KLYSTRONS AND MICROWAVE TRIODES, D. R. Hamilton, J. K. Knipp, J. B. H. Kuper
8. PRINCIPLES OF MICROWAVE CIRCUITS, C. G. Montgomery, E. M. Purcell, R. H. Dicke
9. MICROWAVE TRANSMISSION CIRCUITS, G. L. Ragan
10. WAVEGUIDE HANDBOOK, N. Marcuvitz
11. TECHNIQUE OF MICROWAVE MEASUREMENTS, C. G. Montgomery
12. MICROWAVE ANTENNA THEORY AND DESIGN, S. Silver
13. PROPAGATION OF SHORT RADIO WAVES, D. E. Kerr
14. MICROWAVE DUPLEXERS, L. D. Smullin, C. G. Montgomery
15. CRYSTAL RECTIFIERS, H. C. Torrey, C. A. Whitmer
16. MICROWAVE MIXERS, R. V. Pound
17. COMPONENTS HANDBOOK, John F. Blackburn
18. VACUUM TUBE AMPLIFIERS, George E. Valley, Jr., Henry Wallman
19. WAVEFORMS, Britton Chance, F. C. Williams, V. W. Hughes, D. Sayre, E. F. MacNichol, Jr.
20. ELECTRONIC TIME MEASUREMENTS, Britton Chance, R. I. Hulsizer, E. F. MacNichol, Jr.
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26. RADAR SCANNERS AND RADOMES, W. M. Cady, M. B. Karelitz, L. A. Turner
27. COMPUTING MECHANISMS AND LINKAGES, A. Svoboda
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PART I

HISTORY AND ORGANIZATION OF RADAR ACTIVITIES

Chapter 1

SUMMARY

1.1 INTRODUCTION

In June 1940 Dr. K. T. Compton, chairman of Division D of the National Defense Research Committee [NDRC], established a section to study the applications of microwaves (radio waves less than 5 in. long) to military detection devices. This Section D-1 was headed by Alfred L. Loomis, and he eventually called in as members a group of a dozen university and industrial scientists and engineers. Known popularly as the Microwave Committee, the section continued, with remarkably few changes in personnel, throughout the war, later becoming Division 14 (Radar) of NDRC.

During the summer of 1940 members of this committee investigated the radio-detection developments (now known as "radar") which were being carried on under the supervision of the Army and Navy in this country. During this investigation they became impressed with the fact that it would be of great importance if microwave techniques could be developed and applied to radio-detection equipment. A small group of physicists and engineers worked during the summer of 1940 at the Loomis Laboratories, in Tuxedo Park, New York, exploring methods of generating, detecting and using microwaves. Excellent progress in the exploration of microwave techniques was made, but the results on the whole were discouraging because of the fact that no vacuum tube was available which would generate microwave pulses sufficiently intense for practical pulse-detection equipment.

1.1.1 Report of the British Technical Mission

In the early fall of 1940, a British Technical Mission, headed by Sir Henry Tizard, arrived in this country bringing to Army, Navy, and NDRC officials the full story of the development and use of radar equipment in England. This Mission revealed the critical importance of such equipment in modern warfare and requested the cooperation of the United States in the development effort. Its members also revealed that a group at the University at Birmingham had developed a new form of cavity magnetron which was capable of generating pulses of 10-kw peak power at a frequency of 3,000 mc, or 10-cm wavelength.

The availability of this single device opened up the whole field of microwave radar, and the Microwave Committee at once realized the possibilities and importance of developing this new field.

In addition, the British mission had brought the information that the most urgently needed radio-detection equipment was a set which could be installed in a night-fighter airplane to effect night interceptions of enemy bombers. The British laboratories had outlined the general requirements and specifications for such an equipment, and calculations had shown that with the new magnetron a set sufficiently powerful to detect enemy aircraft at 3 or 4 miles would be feasible.

The U. S. Army Air Forces were keenly interested in this proposal and joined the British in requesting NDRC to undertake the development of microwave *aircraft interception* [AI] equipment.

1.1.2 MIT Radiation Laboratory

The Microwave Committee at once decided to follow the British pattern and set up a special laboratory, manned by physicists and engineers, to carry forward at a rapid rate this specific development.

After investigating several possibilities, the committee members came to the conclusion that the Massachusetts Institute of Technology [MIT] offered the only feasible location for such a laboratory, and the MIT administration was persuaded to provide the necessary space and facilities.

A group of physicists from universities was at once recruited, and several members of the staff of the Department of Electrical Engineering of MIT who had been working at the Loomis

Laboratories during the summer were transferred to the new MIT laboratory. This group of about twenty-five men began active work in November 1940.

In the meantime Dr. E. G. Bowen, a member of the British mission, had outlined to the Microwave Committee the proposed specifications of the projected AI equipment. The Microwave Committee, in order to have equipment and materials ready for use in the laboratory, had given contracts to several industrial laboratories for the development and manufacture of several models of each of the major components of the proposed system (magnetron, pulser, antenna, receiver, and indicator). Thus, in the first days of the laboratory, the basis had been laid for intimate collaboration between it and industrial laboratories which continually expanded throughout the life of the laboratory.

1.1.3 1940 Developments

Within a few days after they assembled the members of the new laboratory, who decided to call themselves the Radiation Laboratory [RL], were at work studying microwave techniques and learning from Dr. Bowen the military and technical problems involved in AI equipment. Dr. Bowen was an extremely fortunate choice for the position of British liaison officer at the laboratory. His long experience under Sir Robert Watson-Watt on radio-detection problems and his intimate contact with the RAF and its military problems made him the chief source of information for MIT-RL in its early days. His wide knowledge and his charming personality quickly won the admiration and respect of the laboratory members, and he exerted a profound influence in the formulation of MIT-RL plans.

Experimental Models

Work on the components of the first experimental microwave system began immediately and by the end of 1940, the first U. S. microwave pulse radar system was ready for operation. Crude as the system was by present standards, it was a remarkable achievement in that it was put together, starting from scratch, within about two months. In that two months' period, also, some of the major components of the first airborne set were well under way, and it was assembled and ready for test by January 1941. In the meantime negotiations with the Army carried out largely by E. L. Bowles, then Secretary of the Microwave Committee, resulted in the formulation of plans for the supply of an experimental airplane for laboratory use and for the installation of additional AI sets in other planes. In fact, by the beginning of 1941, the laboratory was already making plans for its first "crash" program, namely, the building in the laboratory of fifteen AI sets for the early experimental models of the P-61 airplane.

Antiaircraft Models

Within the first two months of its existence, MIT-RL had undertaken two additional projects which had been planned by the Microwave Committee. The first was a microwave radar of high precision for use with antiaircraft guns. Dr. Loomis had proposed the development of the principle of conical scan, which later proved so successful, and a small group was at work studying the problems of radar fire control.

Loran

The third project was that of *long-range navigation* (later called "Loran"), the scheme for which had been outlined by Dr. Loomis. A special committee of Section D-1, under the chairmanship of Dr. Ralph Bowen of the Bell Telephone Laboratories [BTL], supervised various industrial contracts and helped organize the work on this project.

The end of the year 1940, therefore, saw the laboratory embarked on an intense program with a thriving and capable group of some 75 men, working day and night, laying the basis for the great program which was yet to come but was still only dimly foreseen. There was, at that time, some feeling that nine to twelve months of work would see the basic microwave research completed, and the group would then disband. But this was a year before the United States entered the war, and it was before the enormous possibilities of microwave radar were dreamed of.

1.2 1941—EXPLORATION

Performance of First Models. The year 1941 was a momentous one in the microwave art and in MIT-RL history. The laboratory continued to

expand throughout the year, and its personnel nearly reached the 500 mark by the year's end. Early in the year the need for much more space than could be provided within MIT buildings was visualized, and plans were laid for the construction of a permanent building.

The technical development work proceeded with remarkable rapidity. The first experimental radar system operated successfully in January, and its performance improved by leaps and bounds during the succeeding weeks. The first system designed for aircraft installation was operating in early February, and on February 7 tracked a small plane to a distance of 2½ miles. This was the first confirmation that a microwave AI system was practically feasible. By March the range had improved to 5 miles, at which time the system was installed in a B-18 airplane supplied by the Army. In the meantime lighter and improved systems were under way. By the middle of the year the Army had placed a contract for such equipment with the Western Electric Company, and a laboratory experimental set was taken to the Bell Telephone Laboratories [BTL] along with two RL men, who assisted in working out the production design. The laboratory assisted in general development of components of the AI-10 after this time, but BTL carried the responsibility for further development of Army 10-cm AI equipment from that time forward. Eventually this development resulted in the extremely successful SCR-720, which was used extensively by the British and American Air Forces.

High-Frequency Magnetron Development. Many new microwave problems were springing up, however, each month. Almost from the outset the development of higher-frequency magnetrons was a part of the research program. Collaborating with BTL and the Raytheon Manufacturing Company, the magnetron group had 3-cm magnetrons under test by March and the laboratory was already visualizing an AI set using this new higher frequency which would allow much greater compactness in airborne installations. The U. S. Navy soon became interested in this possibility since it was concerned with carrier-based aircraft. By the end of 1941 designs of the preliminary Navy AIA were well under way.

Plan-Position Indicator. Flight tests with the AI-10 equipment had shown its great value in detecting surface vessels when flying over the sea. The first airborne *plan-position indicator* [PPI] was developed to improve the performance of equipment for this purpose, and microwave *aircraft-to-surface vessel* [ASV] equipment was successful almost from the start. With the submarine war growing in intensity, the British were keenly interested in this development, and by the end of the year experimental equipment was being made for trials in England.

Fire-Control Radar. The development of 10-cm fire-control radar proceeded rapidly and in March the first automatic-tracking microwave radar was in operation on the roof laboratory of MIT. The accuracy and reliability of tracking was sufficiently great, even with the experimental equipment, to attract the interest of the Coast Artillery Board, then responsible for antiaircraft gunnery. With its interest expressed, a mobile automatic-tracking unit installed in a truck (the famous XT-1) was ready for trials by the end of the year. This represented a particularly extraordinary achievement since precision, field reliability, and elaborate data-transmission mechanisms had to be designed in addition to the basic radar equipment. The basic soundness of the early design was exhibited by the fact that the production models, which essentially copied it, were still, in 1945, among the best and most versatile ground radar equipments available in the field.

Shipborne Radar. Another major step was taken in 1941 when equipment originally designed for aircraft installation was modified and installed aboard a U. S. Navy destroyer, USS *Semmes.* This was the first microwave radar with PPI presentation to be used on shipboard, and the first tests showed the great value which such a shipborne radar would have. Naval officers were so impressed that by the summer of the year a production order had been placed with Raytheon for what was later called the SG radar, one of the most widely used and successful of all shipboard radars.

Harbor and Coastal Applications. A set somewhat similar to that installed on the USS *Semmes* was installed in a truck for mobile field tests during the year. It was tried extensively at Deer

Island in Boston Harbor as a harbor surveillance set, primarily to collect data on the surface-search problem. When the United States entered the war in December, this experimental set was requested by the Boston Harbor Entrance Control Station and was put at once into service as a day-and-night surveillance set for the Boston Harbor. At the same time the Signal Corps and the Coast Artillery requested the newly organized Research Construction Company Model Shop to build fifty of these sets, designated as the SCR-582. This was a terrific order for a struggling young model shop to take, but after long consideration it was taken and the order successfully completed during 1942. These fifty sets saw extensive use in the field.

Summary of 1941 Research

These are only some of the major exploratory new systems which were developed during 1941. Radar for the control of aircraft armament, for range-finding, for shipboard machine guns, high-power search and height-finding equipment for interception control, and a number of other projects were initiated during the year. In each case the experimental microwave equipment was able to fill a totally new purpose or was superior to previous equipment. By the end of the year microwaves "were here to stay" and were not "something for the next war."

The rapid extension of application of microwaves to military problems was accompanied by equally rapid development of the basic components of microwave radar. Compact pulsers for airborne use were developed; microwave receiver design was enormously improved; TR boxes, waveguide and transmission-line techniques, antenna designs, and indicator designs all went through developments which resulted in very large improvements in performance and reliability.

Although by the end of 1941 not a single microwave set was in combat use, the basis for the new industry had been laid, production orders for many sets had been placed, and extensive trials had proved the value and versatility of microwave techniques. Thus in the space of a single year microwave radar had arrived and was ready to emerge from the laboratory.

1.5 1942—EMERGING FROM THE LABORATORY

Expansion of Facilities. The year 1942 witnessed the most remarkable flowering of MIT-RL activities. This year saw microwave equipment brilliantly successful in combat use, saw a tremendous further flowering of the possibilities of application to new tactical problems, and witnessed further development and perfection of every microwave radar component.

The problems laid out and planned in 1942 are those which occupied most of the laboratory's attention for the rest of its existence. This year also witnessed the most rapid growth in scientific personnel in the laboratory's history. The total personnel employed rose from 450 at the beginning of the year to 1,700 at the end. The new Building 24 was occupied and almost immediately expanded by the addition of five floors, and by the middle of the year a huge temporary building, Building 22, was occupied.

Use in Submarine Warfare. The United States was now at war, and there were immediate personnel reasons on the part of each member of the staff for pushing the work ahead rapidly and effectively. At the beginning of the year an immediate emergency arose with the disastrous success of the German submarines along the Atlantic Coast. The laboratory, in a rush job, converted parts intended for AI-10 equipments into ASV sets, and installed them in ten B-18 planes which formed a coastal patrol squadron operating out of Langley Field. Almost at once these planes were successful in detecting and sinking German submarines, and they, with later planes equipped with production sets, played an exceedingly important role in eventually eliminating the submarine menace from the coastal waters of the United States.

This operational success served to redouble the efforts at MIT-RL. As the year went on, additional operational successes multiplied. The British were planning an intensive campaign against the U-boat in the Bay of Biscay, and for this they used much American equipment. American planes also participated in this campaign, which finally spelled the death of the U-boat as a threat to Allied success.

By the middle of 1942 the MIT-RL had some

twenty system projects on its books, a number which had grown to nearly fifty by the end of the year. During the year, also, the production lines began turning out RL equipment in quantity, and by the end of the year many sets were in large-scale production. Laboratory-built sets, as well as production sets, were serving in many theaters of war by the end of the year.

Production and Design Progress. Within MIT-RL many basic new ideas for microwave applications were developed. The precision bombing-through-overcast equipment, known as Eagle, was mapped out and preliminary experiments begun. The first ideas for a long-range *microwave early-warning* [MEW] set, were laid down, as well as the fundamental principles of the *ground control of approach* [GCA], a set for landing aircraft under conditions of poor visibility. A considerable effort went into the development of airborne fire-control equipment, a field of great complexity because of the multiplicity of types of airplanes and guns; 3-cm equipment for airborne and shipborne use developed rapidly, and the beginnings of 1-cm techniques were well along.

The problems of getting equipment into production were occupying a larger and larger share of laboratory effort, particularly since the large radio companies were soon overloaded with war work, and the laboratory set about the problem of finding and educating new manufacturers. The RL transition office was established to assist in these production problems and rapidly grew to be an invaluable part of the laboratory.

By the end of the year the laboratory had reached full maturity. Its component development groups were now well organized, the system groups were at work on a wide variety of experimental and production equipments, and the engineering and production design activities were reaching a firm footing. The Army and Navy were looking more and more to MIT-RL for assistance in solving tactical problems, as well as for help in supervising production designs. Collaboration with industrial laboratories had grown to very large proportions, and the standard for future collaboration was set by the extraordinary achievement of the Philco Corporation in bringing a laboratory set to full-scale production in nine months by making the most extended use of MIT-RL facilities and skills. The stream of scientific visitors to and from England which began with a trickle in 1941, continued to swell during the year, resulting in the most intimate exchange of information and ideas between this country and the British laboratories.

1.4 1943—THE RISING TIDE

Field Applications. The year 1943 might be characterized primarily as one of engineering and production. The basic ideas already developed were sufficient to keep the entire resources of the laboratory fully occupied in working them into practical form, in working on production designs, and now, for the first time, in assisting the Army and Navy in problems of training and using the large volume of production equipment in the field. Every radar component and part, hundreds in number, went through engineering improvements and expansion in production facilities. By June 1943 nearly 6,000 radar sets of RL design had been delivered to the Army and Navy, 22,000 were on order, and production was climbing past the rate of 2,000 sets per month of all types. The total dollar value of orders for the Services had by that time grown to three quarters of a billion dollars. Production mounted rapidly during the latter half of the year, and equipments with trained personnel were reaching the theaters in large quantities.

This year also saw the establishment of the British Branch of the Radiation Laboratory [BBRL], an organization which continued to grow in size and effectiveness until the end of the European war. Operational success in the field had now become commonplace. The naval battles in the Pacific were making extensive and successful use of the SG and other equipment. The campaign against the submarine by both Army and Navy Air Forces was in full swing, with 10- and 3-cm equipment playing a prominent role. Experimental blind-bombing equipment was introduced to the Eighth Air Force, and the first use of it in Europe occurred in November. The SCR-584 accounted for itself brilliantly in the Italian campaign and in the Pacific. Improved models of almost every kind of equip-

ment were being designed to meet the demands of field experience or new demands in the changing war.

Personnel Problems. The large number of different types of equipment, the variety of production and engineering problems, the growth of field problems, all put an ever-increasing burden on MIT-RL personnel. The total number of employees rose during the year from 1,700 to 2,700. A large share of the new acquisitions, however, were nontechnical employees, or were young and inexperienced. The administrative load placed on the senior scientific personnel became extremely heavy, and more and more responsibility devolved on younger staff members. Fortunately a considerable group of young but extremely able leaders developed.

Application of Loran. Ever since the beginning of the laboratory the Loran work had developed and the year 1943 saw Loran introduced in wide-scale use in the Atlantic as an important navigational aid. Stations were installed with MIT-RL help in extremely inaccessible and difficult locations in the northwest Atlantic area.

As the year ended plans for the invasion of France were being prepared, and the attention of the laboratory turned to the problem of supplying urgently needed equipment for that theater.

1.5 1944—RADAR IN THE FIELD

Field Service Bases. The year 1944 saw a large share of the laboratory's effort devoted to direct service in the field and to the rapid manufacture of experimental equipments for immediate field use. BBRL worked intimately with the U. S. forces in Europe assisting in the use of new equipment and adapting equipment on hand to new uses as the needs arose. At home RL responded to urgent calls from BBRL for new equipment, attachments and modification kits. As an example, five laboratory-built MEW sets were sent to Europe plus additional indicators, beacon kits and many other attachments which helped this equipment play an important role in that war.

After D-Day BBRL moved much of its effort to the Continent and shortly after the fall of Paris set up an advance service base there, to remain in closer touch with the field officers. As the Battle of France culminated in brilliant and rapid success, and the war in Europe appeared to be well on its way to completion, the attention of MIT-RL swung to the Pacific war, which was also reaching its climax. This swing was partly checked by the Battle of the Ardennes Bulge which required intense consolidation of the efforts in Europe. Nevertheless, radar in the Pacific, particularly in the hands of the Navy, commanded increasing attention and met with increasing success.

Development of AEW. In early 1944 the U. S. Navy proposed to the laboratory the most ambitious program ever undertaken, the development of *airborne early-warning* [AEW] equipment. This extraordinarily difficult job was only a dream in March 1944, but its possibilities had been proved by the end of the year, and in August 1945 a carrier was completely equipped with model shop equipment and trained personnel in readiness for the Pacific campaign.

The year 1944 also proved the *versatility* of microwave equipment. The set designed for antiaircraft fire control became an important link in the control of aircraft in tactical air operations. The MEW, designed as an early-warning set, proved to be a powerful tool in the control of both tactical and strategic air forces. Many other sets were revised by RL personnel in the field to meet new tactical requirements, and the laboratory was called on to produce many attachments and modifications for gear already in the field.

This year saw also the final perfection of 1-cm techniques, and orders were placed by both the Army and Navy for airborne equipment at this wavelength.

1.6 1945—THE END

Pacific Activities. Early 1945 saw the war in Europe reaching its climax, with BBRL personnel more active than ever in urgent field problems there. The war in the Pacific, however, seemed destined to go on for two more years. Longer term projects for this theater were pushed intensely, particularly as Japanese suicide attacks developed serious proportions. As the war in Europe ended, BBRL personnel were quickly returned home, and many of them were promptly dispatched to the new Pacific branch of OSRD which was being set up in Manila.

By this time Loran chains had been extended throughout the Pacific, throughout the Atlantic, over the Continent of Europe, and into the China-India Theater. A new type of Loran, operating at lower frequency, had shown promising results, and an operational chain was being prepared to give improved navigational facility over the Japanese islands. The long-term and extremely large effort which had gone into the Mark 56 fire-control system for naval ship use reached its culmination in successful trials, and a large order was placed for equipment. The AEW project, employing the largest group ever assembled on a single project in the laboratory, went through its trials, and, as has been mentioned, equipments produced by the model shop were just ready for action as the first atomic bombs were dropped and the Pacific war came to its dramatic end.

Termination of Project. At this time, on instructions from OSRD, the laboratory already had begun its process of demobilizing the long-term research activities and had for some time been undertaking no new long-term projects. The end of the war brought all activities to a sudden halt, and the process of tearing down in five months what had been built up in five years began.

1.7 WHY MICROWAVES?

Advantages of Microwaves. At this point it is well to stop and review precisely the factors which made microwave radar, as compared with longwave radar, so important. There have been frequent suggestions of rivalry between microwaves and long waves, with implied disparagement of one or the other. This is unfortunate, for actually there are applications in which each is best fitted for reasons of economy, coverage, weight, and other factors. Furthermore, it is no disparagement of the longwave equipments, developed before the days when microwave techniques were available, that they were in some cases superseded by microwave equipment.

The advantages of microwaves for a large number of radar applications depend upon certain fundamental physical facts. These facts are connected with the two well-known physical phenomena of *diffraction* and *interference.*

Diffraction. The phenomenon of diffraction, for our purposes, means that when electromagnetic radiation passes through an aperture or emerges from an antenna or a reflector, the beam which results is not as sharp as would be predicted from the ordinary laws of geometrical optics. In fact, some radiation spreads out in all directions, but most of it is concentrated within a beam the width of which is the greater the longer the wavelength and the smaller the aperture or antenna. Hence, with a given sized antenna structure, the beam grows steadily narrower as the wavelength is reduced. Thus, microwave radar means radar in which the beam is relatively sharp. Narrow beams in radar have a number of advantages:

1. The available power is concentrated in a smaller region in space, and hence, other things being equal, greater range of detection is possible with a given amount of power.
2. Narrow beams give a possibility of higher accuracy in determination of the angular bearing or elevation of a target, an accuracy which is important in many applications.
3. Narrow beams allow higher resolution, which means that two targets close together can be distinguished as two, rather than giving a single, unseparated signal. In other words, a narrow beam gives radar additional "sharpness of vision," a factor which is of predominant importance in such applications as blind bombing.
4. Narrow beams increase the ratio of the target signal to unwanted signals caused by ground reflections, sea waves, clouds, or enemy-created clutter.
5. Narrow-beam radar is harder for the enemy to jam by any method, partly because the jamming source must be in the narrow beam itself to be effective, and partly because the amount of power required for jamming must be comparable to the power concentrated in the beam itself.

Interference. The phenomenon of interference, which also depends fundamentally on wavelength, is a factor to be considered in certain radar applications. The most important of such applications is concerned with the propagation of radar beams over the surface of water. In this case (unless the beam is so sharp and so pointed that none of it strikes the water) the phenomenon of interference always appears be-

tween the beam going directly from the radar antenna to the target and that which is reflected from the surface of the water. Depending on the height of the target and, hence, on the difference in path traversed by these two beams, the two beams will interfere with each other to produce either destructive or constructive interference. Because of the change of phase of 180 degrees which occurs in the reflection itself, this means that one always gets destructive interference along the surface of the water.

Indeed, a pattern of maxima and minima is set up, the structure of which depends upon the height of the antenna above the water and upon the wavelength. With low antennas shorter-wavelength radiation hugs the water more closely, and the pattern of maxima and minima is such as to afford less likelihood of a target being missed. As a result, radar used on shipboard for surface search and detection secures great advantage by the use of short wavelengths since objects on the surface can be detected very much further away.

Versatility of Application. Finally it should be mentioned that since, for a given size of beam, an antenna for short waves is smaller than for long waves, problems of installation in cramped quarters on shipboard and in aircraft become easier, and it is also more convenient to design specialized antennas for a variety of purposes, antennas which give specially shaped beam patterns and thus allow a greater versatility in radar applications.

The amount of refraction or bending of radio waves by varying water vapor densities in the atmosphere also varies with the wavelength. There are frequent occasions when very short waves are refracted around the curvature of the earth to a considerably greater extent than long waves. This may be either an advantage or a disadvantage, depending on circumstances, but it is a factor to be considered.

The design of a radar set is a complex problem and the factors named above are not always of sufficient advantage to overbalance other factors which may be present. Nevertheless, each of the advantages herewith listed for microwaves has played an important role in enabling certain equipments to do things not previously possible, or, in many cases, to do them better. The advent of microwaves in the radar field can, therefore, be regarded as one of the major achievements which made radar such a powerful tool in World War II.

1.8 A SURVEY OF MICROWAVE APPLICATIONS

The complete story of the development and use of all the microwave equipment during the war is a long one indeed. RL participated in the development of some 100 different types of microwave equipment which were used in small or large quantities, or were nearly ready for use as the war ended. These equipments had their effect on every aspect of air, land, and sea warfare. Even as the war ended it was clear that while microwave radar had already profoundly affected many tactical operations, a still more profound effect on tactical and strategic plans could have been expected if the war had continued a year or two longer. Important as were the contributions of microwave radar, the ultimate possibilities have not yet been achieved. A few of the highlights of their important use are worth brief mention.

1.8.1 In the Air

The first microwave application was in airborne use and RL has always been largely "air minded." Of the dozens of airborne radar equipments, there were few successful ones which did not operate at microwave frequencies, the U. S. Navy ASB, an airborne search set, and the Army-RCA Shoran bombing set being the main examples. Below are listed some of the major airborne applications.

Aircraft Interception

The 10-cm AI equipment in the form of the SCR-720 became standard equipment for the U. S. Army and the RAF nightfighters. This application proved of far more importance to the British than to the U. S. Forces, and they put a correspondingly large effort on the problem. U. S. Navy carrier-based nightfighters were equipped with 3-cm AI equipment which had many important successes.

Surface-Vessel Search

Equipment of the ASV type for detection and destruction of surface vessels and submarines played a role of critical importance in the war. Many different types of sets were developed for this purpose. The first were 10-cm equipments, of which the SCR-717 and the Navy ASG were the most widely used. Later 3-cm equipment, of which the Navy ASD was the first, saw still wider use, and 3-cm equipment eventually came to be used almost universally by the Navy.

Equipped with a computing attachment for low-altitude bombing, U. S. Army planes with SCR-717 equipment accounted for huge quantities of enemy shipping in the Pacific area. According to General Kenney, two squadrons alone accounted for nearly one million tons of Japanese shipping, all destroyed at night and all completely by radar detection and attack. The major contribution which ASV equipment made to the war against the submarine has already been mentioned.

Blind Bombing

The British were the first to use airborne radar for blind bombing of German targets at night. The U. S. Air Forces had adopted a policy of precision daylight bombing, but it was not many months before their experience in cloudy Europe convinced them of the necessity for equipment for bombing through overcast. A large number of planes in both the Eighth and Fifteenth Air Forces were eventually equipped with the so-called H_2X equipment, and all of the B-29's had this as standard equipment.

During the winter months in Europe a preponderant part of the bombing was done through overcast with radar instruments. During the last months of the war high-precision equipment of the Eagle type was used by squadrons of B-29's over Japan and turned in spectacular records for precision attack. One complete wing of B-29's was especially equipped with Eagle equipment, and a second wing was beginning to arrive in the theater as the war ended. Blind bombing did not approach visual bombing in accuracy, but continual improvements were made as training problems were better understood, as operational planning became more complete, and as computing mechanisms were developed. Great improvements in radar bombing precision could still be attained with further development of 1-cm equipment and more highly perfected bomb-release computers.

Airborne Fire Control

Although a large development effort went into radar for the control of airborne guns, both the German and Japanese Air Forces were destroyed without extensive employment of such equipment. The sets developed ranged from simple range-finding sets to complete automatic-tracking equipment for tail turrets. A special range finder for use with 75-mm cannon on the B-25 had considerable use and success. A number of B-29's were equipped with a manually operated tracking direction- and range-finding radar for the tail turret guns. If future air wars are fought, radar gunnery will, no doubt, play an important role, for the techniques are well understood now, and further development is possible.

Air Navigation

Bombing and ASV sets have proved invaluable aids to air navigation. It was the navigational aspects which made the sets popular with their crews. Navigational equipment for troop-carrying planes provided by a converted ASV set saw service in the European Theater, and orders for a more simple light-weight navigation set had been placed and production just begun as the war ended.

Beacons

Radar beacons are a valuable adjunct to airborne radar. Beacon bombing equipment of two different types saw operational use. In one, the "H" system, beacons on the ground were used in conjunction with the airborne microwave radar. In the other, a beacon in the aircraft responded to radar stations on the ground in the microwave "Oboe" system. Beacons to mark airfields and other important landmarks as navigational aids proved of considerable importance. Portable beacons carried by paratroopers to mark dropping zones for oncoming planes also opened up a technique of great possibilities and one which saw successful operational use.

1.8.2 On the Ground

The applications of ground-based radar are so many and so varied that it is difficult even to classify them. A few of the major categories in which microwave techniques turned out to be of value and in which MIT-RL put considerable effort are discussed in the following text.

Air Defense

The complete air defense problem involves:

1. Early warning of approaching airplanes.
2. Control of intercepting fighters.
3. Antiaircraft fire control.

Early Warning of Approaching Airplanes. The first and the most widely used early-warning equipments which served in large numbers all through the war was the SCR-270, developed before the war by the U. S. Army Signal Corps. Because of the availability and success of these equipments, and because of the low-power level of early microwave gear, MIT-RL did not undertake development of microwave early-warning equipment until 1942. By this time high-powered microwave magnetrons were available, and advantages in the higher resolution of microwave equipment were more fully realized. The result of nearly two years of intense development effort was the so-called MEW equipments previously mentioned, which got into commercial production shortly before the end of the war. Laboratory models of these equipments, however, served in Europe and in the Pacific primarily as equipments for the control of friendly aircraft rather than for the detection of enemy raids.

Control of Intercepting Fighters. The control of intercepting fighters requires radar equipment of higher precision than that used for early warning, and requires, in addition, mechanisms for determining the height of friendly and enemy planes. Actually the MEW equipment, with an auxiliary height finder, proved to be the best combination. More compact 10-cm equipment, giving height and azimuth on individual planes, was developed and put into production as the SCR-615 which saw limited use.

A similar set adapted for shipboard use, however, was widely employed. This employed the conical-scan principle, also used in the antiaircraft gunnery radar discussed in the next paragraph. Later height-finding techniques used the so-called Beavertail beam which scanned in elevation giving heights of all planes within a given sector simultaneously. Finally the V-beam principle was perfected allowing continuous height finding, and scanning. The first models were being completed in August 1945.

Antiaircraft Fire Control. The major effort in the laboratory on the antiaircraft fire-control radar was the SCR-584 already mentioned. This automatic-tracking radar could follow individual planes with an accuracy of around one-tenth of a degree and a range accuracy of a few yards feeding present-position data continuously to a suitable computer. This equipment became standard equipment for most antiaircraft gun batteries, and, in addition, toward the end of the war showed many possibilities for adaptation to other unanticipated uses.

Control of Air Operations

Ground-based radar which gives a wide and accurate view of air operations opens up the possibility of the control of such operations on a large scale. MEW radar, the SCR-584, plus a variety of special attachments such as computers and beacons, etc., give a remarkable facility for this purpose.

As the war ended equipment using the V-beam principle was being produced in small quantities, and would have given even more complete facilities for this purpose. The control of both tactical and strategic air operations in Europe was carried on in bad visibility with the 584 and MEW, the latter being supplied straight from RL. Airborne beacons were an important auxiliary for ground control, extending the range on small planes and insuring proper identification. This type of technique carries over directly into the control of peacetime airway traffic, and the use of radar aids in this field shows great possibility.

Ground Force Operations

Radar for the use of ground forces in their various problems never got into wide use in this war because the techniques required were mostly beyond the state of the art. Experimental radars for the detection of gun and mortar shells, and for the detection of moving vehicles and person-

nel were produced in small quantities and showed interesting possibilities.

AIRCRAFT LANDING

The landing of aircraft in bad visibility on airfields presents a problem in traffic control and precision location for which radar aids are particularly suitable. The *ground control of approach* [GCA] system is a first and successful step toward the solution of this problem. The precision and resolution available with microwave techniques made such a system possible for the first time. Some of the production versions of this equipment turned in spectacular records for saving planes attempting to land under unfavorable conditions.

1.8.3 At Sea

With the exception of equipment for long-range air warning, practically every radar set on modern ships is a microwave set. These sets perform a wide variety of complex functions.

FIGHTER CONTROL

Radar for this function must give precise and continuous information on location of friendly and enemy aircraft over a wide area. Until recently, radar techniques were not available to meet all the necessary requirements of such equipment. A set designed in the laboratory, however, known as the SM, has been widely and successfully used, together with its lighter-weight successor, the SP. Considerable further study of the problem and development of techniques led finally to the design of the SX, which was getting into production as the war ended. This is the first shipboard set to give full, accurate data on bearing, distance, and height of all planes continuously over a wide area.

SURFACE SURVEILLANCE AND NAVIGATION

The first application of microwave equipment to shipboard use was for the location of surface vessels, surfaced submarines and other objects on the surface of the water, as well as nearby land masses. This opened up tremendous new possibilities in the maneuvering of naval forces in conditions of low visibility, and large numbers of equipment of this type were adapted to every kind of naval vessel, and were produced and installed on practically every combat vessel of the U. S. Navy. Such equipment, with suitable attachments, was particularly useful in the accurate navigation required in amphibious landings.

FIRE CONTROL

The control of naval gunfire requires accurate position data to be fed continuously to computers. The requirements are particularly severe when the targets are aircraft. BTL carried the major burden of designing radar fire-control equipment for the U. S. Navy throughout the war, and as soon as techniques became available, BTL engineers made use of microwave frequencies.

MIT-RL assisted at various points in this work, and in 1943 undertook intensive development of a completely new combined radar and computer for the fire control of 5-in. or smaller guns for either surface or antiaircraft fire (Gun Fire-Control System Mk 56). Although the final laboratory prototypes were not completed until November 1945, the Navy has authorized post-war production and installation of this equipment.

1.9 THE ORGANIZATION OF THE RADIATION LABORATORY

To understand the way in which the Radiation Laboratory was organized and operated it is necessary, first, to review the various higher authorities to which MIT-RL was responsible and the channels through which this responsibility operated. Ultimately, of course, the director of OSRD was responsible for the entire scientific, financial, and administrative operation of OSRD activities. Actually, after broad policies were formulated, the scientific program and its administration was delegated to NDRC, but administrative and fiscal matters were handled by the contracting officer of OSRD. NDRC, in turn, divided up the field into some nineteen divisions, and made the chief of each division responsible for the scientific activities coming within his area. Since MIT-RL operated under Division 14, the chief of this division, Dr. A. L. Loomis, was responsible for setting general policies in regard to the scientific program of the laboratory. The Division 14 committee served as a sort of board

of directors, passing on general policy matters and on matters of budget policy. Thus matters of broad general policy came to the director of the laboratory from the Division 14 committee. More specific instructions came directly from the chief of Division 14, and detailed instructions and authorization on administrative matters were handled by the executive secretary of Division 14.

Contractual matters for which OSRD was responsible were handled through a contractual arrangement between OSRD and MIT, in which MIT was charged with the responsibility of administering and operating the laboratory devoted to work specified by Division 14 of NDRC. MIT assumed the responsibility of operating the administrative and financial affairs of MIT-RL in such a way as to meet the rules and requirements of government contracts. The Division of Industrial Cooperation [DIC] served as the agent of the MIT administration for managing contractual matters, and DIC in turn delegated to the director of the laboratory responsibility for conducting its administration in line with government and MIT policy.

This mechanism through which OSRD operated is reviewed in order to point out that the director of MIT-RL was responsible to Division 14 for the general scientific program of the laboratory and for general administrative matters, and simultaneously was responsible to the president of MIT for matters connected with operations on the MIT campus and for matters connected with contractual obligations.

When MIT-RL itself was first established, the organization was exceedingly simple and informal. There were five components of the first radar system which needed to be developed, so five groups were formed to carry on the work. As new problems came up new groups were added. Coordinating mechanisms were scarcely required at first since the entire group was small and, moreover, was an extremely congenial one. Eventually the size and diversity of MIT-RL outgrew the simple organization, and in 1941 the division structure was established, which persisted until the end. Under this organization the laboratory was divided into eleven (later twelve) major divisions, with a division head in charge of each. Three of the divisions had to do with business affairs, buildings and maintenance, and personnel; one had to do with advance research; two were devoted to component development; and the remaining divisions were devoted to specific classes of system problems. Thus one division was devoted to airborne application, one to fire control, one to beacons, one to Loran, and so on. The director and associate directors, the heads of the various divisions, and the associate heads, constituted the steering committee of MIT-RL which operated as a sort of cabinet. It was in this committee that all major problems concerning the program of the laboratory were discussed. The conclusions reached by the committee were put into direct effect by its members, who had executive responsibility for the laboratory work. Each division was divided into groups devoted to specific problems within the area of the division.

It was the function of the system groups to be informed fully in regard to the tactical problems in their respective fields. They kept informed on these problems, of course, through discussions with military and naval officers, with civilians returning from the field, and by means of reports received from a variety of British and American agencies. They were also responsible for being generally informed on the technical possibilities of radar component design. Thus, as new tactical requirements arose, or as new technical developments came along, it was possible for the system divisions to propose an overall design for a new radar equipment to meet a specific tactical need. In collaboration with military personnel they would write the general characteristics for the proposed equipment, and in collaboration with technical personnel, write the technical characteristics. The component groups within MIT-RL would then be requested to develop the components required for the new system, and to deliver experimental models to the system group. The system group named a project engineer for each system who was responsible for coordinating the design of the various components; for assembling them into a final equipment; for providing for the general mounting and assembly of the final equipment, and for its laboratory, field, and service tests; for following through production design; for assisting in introduction of the equipment in the field; and for working on improvements, attachments, and modifications to

keep the set adapted to its tactical requirements. It was the job of the component groups, on the other hand, to take care of all problems connected with the development, design, engineering, and production of the individual component parts of the equipment. Thus vacuum tubes of various types might need to be developed, engineered, and put into production. Special circuit elements, pulse-forming lines, specially wound potentiometers, and dozens of other items might have to be designed and put into production by a firm which could later serve as subcontractor to supply this part for the Army or Navy prime contractor. The production design of the transmitter, the antenna, the receiver, the indicator, and other major components was also the responsibility of a component group, which worked intimately with the engineers and the prime contractor on the final design. As often as not it was new developments in the component groups, higher-powered tubes, improved circuits, etc., which made possible sets for new tactical uses or which stimulated major improvements in existing equipments.

The net result was that the design of the new radar set was a job which normally involved a very large number of individuals in a large number of groups throughout MIT-RL. The system project engineer had at his command an enormous supply of highly specialized talent and experience in the design and use of almost every detailed part of a complete system. Through the medium of the component groups, experience acquired in airborne equipment became available, where applicable, to ground and ship equipment, and vice versa. The component groups served as a large reservoir of research, development, and engineering experience, upon which every new radar depended, and from which it drew the best possible ideas for design.

The back-and-forth cooperation between the system and component groups was one of the major factors in MIT-RL operations and in its success.

1.10 COLLABORATION WITH MANUFACTURERS

The story of the intimate collaboration between MIT-RL and scores, and eventually hundreds, of manufacturers, subcontractors, and vendors throughout the entire industry is far too elaborate and detailed to be related here. It was anticipated in the early days that this problem would be a relatively simple one. MIT-RL would develop a piece of radar equipment, prepare a breadboard model for trials, and then, if accepted by the Army or Navy, turn this model over to a manufacturer, who would take full responsibility for carrying it from the breadboard stage to final use in the field. Such a simple picture turned out to be the farthest possible from the truth. Rather, one should say that this technique was possible only in a very few cases, and these were mostly cases where the equipment was manufactured by the Western Electric Company. In this case the entire facilities of this company and BTL, together with their many subcontractors, were available to tackle the problem and carry it through to completion. Even in this case, however, close collaboration between MIT-RL and BTL was practiced.

In general, there were very few companies with the facilities and experience required to carry through a complex new radar equipment from the laboratory stage to full production. It was not only that the radar equipment itself was new, but scores of parts and components associated with it were also new such as new vacuum tubes, new electric circuit components, new dielectrics, new mechanical parts, dozens of types of "plumbing" fixtures and parts for the radio-frequency portion. All these things in general were manufactured by subcontractors rather than by the prime contractor, and it was the task of the research laboratory to see that all these component parts were designed and put into production by suitable subcontractors all over the country. In addition, test equipment in this field did not exist in the early days. Equipment had to be manufactured for laboratory development work, for factory tests and inspection, as well as for test and inspection work in the field. All this equipment had to be designed, developed, and put into production independently of the production of the radar equipment itself.

This meant that the research laboratory had to have contact with literally hundreds of manufacturers, each of whom was working on the design and manufacture of some particular part or com-

ponent of a radar equipment, or of an auxiliary equipment associated with radar development work and manufacture. A manufacturer of automobiles manufactured precision antenna mounts for the SCR-584. A producer of locks went into production on 3- and 10-cm waveguide elements and fittings. Each of these manufacturers had to be introduced to the problem, had to train his engineers to work out production methods, had to be supplied with detailed specifications plus necessary test equipment, had to be given initial educational orders to get production under way in advance of larger Army or Navy orders, had to be assisted in the design of special tools, and often even had to develop new methods of packing and shipping.

There was no single fixed pattern for handling the liaison between the MIT-RL and the manufacturers and vendors. In general, the transition office, which was a branch of the office of the director of the laboratory (and which worked closely with the OSRD transition office), explored the industrial field to locate manufacturers throughout the country with special talents or experience or facilities for various types of manufacturing work. This office maintained a list of the plants investigated together with current records of their production loads and available engineering and manufacturing facilities. When a new part or piece of equipment required manufacturing facilities, the technical men consulted the transition office, and with its help selected the most promising manufacturer. Needless to say, Army or Navy clearance of the manufacturer had to be processed if the equipment had to be classified as secret or confidential.

Furthermore, the procurement agencies of the Army and Navy also had to agree that the chosen company would be a suitable one for subcontracting on orders should they later materialize. When suitable contractual arrangements had been made, the company would send its technical men to MIT-RL for a period of indoctrination and discussion of the new problem. They secured from MIT-RL complete information, drawings, reports, specifications, and other data having to do with their manufacturing job, and, when necessary, were told how the particular component they were to make fitted in with others so that they would know what features of the design were particularly critical. The company engineers would then prepare their own drawings for the equipment in question, submit them for the approval of the laboratory engineers until designs approved by all concerned were finally worked out. Prototype samples would usually be manufactured and tested before production lines finally were set up. Where necessary the cognizant MIT-RL group maintained a continuous test and check of the production units. In the case of manufacturers chosen by the Army or Navy as prime contractors for a major piece of radar equipment, the collaboration became a three-way one between MIT-RL, the contractor, and the Army or Navy bureau or branch concerned. In this case usually joint coordinating committees were set up with representatives of the three groups. These held frequent meetings working out problems of general design, schedules, choice of subcontractors, specifications for parts and performance, and the scores of other matters that were required in order for radar equipment to meet Army or Navy specifications and requirements.

In certain cases a prototype equipment made at the laboratory would be transferred to the manufacturer's plant, where the task of whipping it into a production design would be carried out with frequent short and long visits both ways between contractor's representatives and MIT-RL representatives. In other cases manufacturer's representatives would spend weeks, or even months, at the laboratory assisting in working out the design of the first prototype model in order that the job of converting it into production designs would be less involved and so that the manufacturer's own techniques and desires could be incorporated right into the early laboratory models. The net result was that at least during the last two years of operation of MIT-RL manufacturer's engineers were generally in on the project almost from its initiation until the end, and MIT-RL research men followed it through the manufacturing design and production process, and finally into the field.

1.11 COLLABORATION WITH THE ARMY AND NAVY

From the day the laboratory was organized close collaboration with the Army and Navy was

a watchword. The relations were always as informal as was possible. MIT-RL did not await formal requests for undertaking projects, and never hesitated to propose new ideas for projects to Army and Navy representatives. On the other hand, the Army and Navy representatives never hesitated to discuss their problems informally with MIT-RL, and in this way nearly always came to general agreements before formal project requests were passed.

The Navy was the first to recognize rather formally the necessity for liaison with the laboratory, and established in 1941 a Navy liaison office. Starting with one officer, this office grew eventually to have a permanent staff of some thirty officers, with temporarily attached project engineers running to an additional thirty or forty officers. Shortly afterwards the Signal Corps established a similar liaison office, and later, when the Air Force took responsibility for radio and radar development, an Air Force office was also set up. These liaison offices were a tremendous help on both sides. They handled all the more formal relations, in addition aided greatly in establishing informal contacts and arranging for visits. Also members of MIT-RL sat as members of committees of the Joint Communications Board of the Joint Chiefs of Staff, and MIT-RL frequently organized special civilian committees to consider various problems and requested Army and Navy membership. A measure of the extensive contacts with the Army and Navy is the fact that in early 1945 an average of fifty officers came to MIT-RL each day for long or short visits, discussions, and conferences. This did not include the many officers, sometimes running to 150, who were here on extended visits for training purposes or for rendering assistance on particular projects.

The most important point which MIT-RL stressed in its relation with Army and Navy representatives was that the Army and Navy representatives come to MIT-RL not with technical problems for the design of an equipment of certain size and weight, or with certain power requirements, but rather that they bring to MIT-RL full information on the tactics of operations which were of importance and for which radar aids might be of use. This gave MIT-RL full access to information on the success and failure of various tactical methods. After acquiring a full understanding of the military problem, it would then be the job of the technical people in the laboratory to evolve suggestions and ideas for the best solution to the problem which they could visualize. The laboratory then would come up with a proposal for the technical design of equipment, accompanied, possibly, by proposals for the new tactics which would have to be adopted to make best use of such equipment. A thorough analysis of tactical and technical problems would then ensue until sometimes after weeks of consideration and discussion a final solution or method of approach would be agreed upon. From that time on the technical design of the equipment was left largely to the technical men in the laboratory, who served, in a sense, as the Army's or Navy's own technical consultants on the problem.

Usually the relations were not so simple as this, but this broad principle became more and more to be accepted by all concerned, and many of the most spectacular achievements in the radar field resulted directly from this type of approach. This method of operation emphasized the partnership between the civilian scientist and the fighting Services, and got away from the suggestion that the civilians were working for or under the direction of the Army or Navy. This established a different relation between the Army and Navy and MIT-RL than was possible between the Services and their commercial contractors whose job was to work for the Navy or Army to receive remuneration for services rendered. This is a suitable relationship in the procurement of equipment. It is hardly a suitable one for working out new research problems.

1.12 COLLABORATION WITH THE BRITISH

A major feature of the laboratory's activities from the earliest days until the end was the intimate collaboration with the various British agencies involved in design, development, and use of radar. This collaboration began with the arrival of the British mission, headed by Sir Henry Tizard, in September 1940. It was this mission which revealed the development of the cavity magnetron and which outlined the urgent necessity for microwave AI radar equipment,

the laboratory's first project. As previously indicated, a member of this mission, Dr. E. G. Bowen, remained at the laboratory for something over two years. Practically all the early concepts of the laboratory as to the techniques for using microwaves, as well as their military applications, came from Dr. Bowen. Through him also the latest information on British developments kept coming to the laboratory, and he transmitted the latest information from this country to the British. Later on, Dr. D. M. Robinson succeeded Dr. Bowen as British liaison representative at the laboratory, and he carried on this intimate liaison in an equally effective fashion. It would have been difficult to have chosen two more able and personable representatives of British scientists. They won the confidence of the laboratory personnel and thereby exerted a great influence on laboratory work.

The establishment of the OSRD office in London was a major step toward increasing close British liaison on the entire scientific front. Radar problems immediately occupied a great deal of the attention of this office and continued to do so throughout its history. An MIT-RL representative was sent as a regular member of this office in the early days, and from that time on at least one member of that office specialized on radar problems.

Early in 1941 Dr. K. T. Bainbridge was the first of many MIT-RL visitors to study at first hand the technical and operational problems in Britain. As all other scientific visitors after him, Bainbridge was greatly impressed with the quality of the work going on in England, with the generosity with which all information was supplied by the British scientists and military representatives, and by the urgency of the operational needs for improved radar equipment of various types. A great stream of MIT-RL visitors went to England during 1941-1943, and thereafter the British Branch of the Radiation Laboratory [BBRL] carried the liaison forward on a still larger scale. The existence of the London office of OSRD made all this possible. It furnished a headquarters in England for MIT-RL representatives, and members of the office were invaluable in guiding representatives to proper agencies, laboratories, and personalities in the British radar picture. Great credit goes to the two men who served in succession as head of the London mission, Frederick L. Hovde and Bennett Archambault. Through their efforts and the efforts of their staff all significant British reports in the radar field were quickly collected and forwarded to this country, where they were eagerly read by RL members. Especially urgent items were transmitted by cable, and later by teletype.

In the meantime many British visitors came to this country with latest information, samples of equipment, and reports on recent developments.

Through these visitors in both directions, through the transmission in both directions of reports, and through the exchange of information by cable it can be said that both British and American scientists were always fully in touch with each other's work and that new ideas arising on either side were quickly incorporated into the development work on the other side. There is hardly a feature of modern microwave equipment which does not contain a multitude of both British and American ideas, and, indeed, hardly an idea arose on either side which could not trace some of its aspects back to suggestions received from across the Atlantic.

The main scientific liaison between the two countries in the radar field was between MIT-RL and the Telecommunications Research Establishment [TRE], a laboratory set up by the Ministry of Aircraft Production. This laboratory, like MIT-RL, drew its staff largely from university physics research laboratories throughout England. Hence the point of view and method of approval of TRE and MIT-RL were always nearly the same, and a quick and intimate understanding between the two groups always existed.

Two other large laboratories, however, were also involved. These were Air Defense Research and Development Establishment [ADRDE], located also at Great Malvern, and the Admiralty Signal Establishment. The former was operated under the Ministry of Supply and was devoted to Army problems, while the latter, of course, dealt with problems of naval radar. Since MIT-RL worked in these fields also, intimate contact with these two laboratories was kept up. It was largely because these organizations were smaller and were less involved in fundamental micro-

wave development than TRE that the relations with TRE were more extensive.

Partly because the relations between the civilian research establishments and the corresponding Armed Services were so intimate, RL contacts with the British Army and Navy and the RAF were also very close. British officers were always extremely helpful, frank, and intelligent in discussing the applications of radar to military problems. Discussions with them, visits to their radar stations, to operational airfield, and headquarter agencies, contributed very greatly to the understanding by RL members of operational and military problems met with in the field. MIT-RL owes a debt of gratitude to many British officers at all levels with whom its personnel established the closest working relations. Many of these officers visited MIT-RL at Cambridge, Massachusetts, during their visits to the United States, and further cemented ties of mutual understanding and friendship.

Liaison with radar experts in the other British dominions, while on a smaller scale, was equally friendly. There was continual interchange of information with the National Research Council at Ottawa and its various members, a number of whom spent considerable time in RL in the early days. Liaison officers from Australian and New Zealand agencies also kept in close touch with the work at MIT-RL through frequent visits.

To sum up, the liaison with British agencies in the radar field was a major feature of MIT-RL work, and, indeed, a major feature of the entire radar enterprise of the Allied nations. Not only in MIT-RL, but also in the various branches of the U. S. Armed Forces and in the great American industrial laboratories, British-American collaboration was continually emphasized and was always effective.

1.13 FIELD SERVICE

Possibly the most unique and far-reaching aspect of the activities of RL was its field service, defined as work directly with U. S. Army or U. S. Navy agencies at locations outside of the immediate vicinity of Cambridge, Massachusetts. It could be divided into domestic field service and foreign field service.

Domestic field service included the very large amount of work done at U. S. Army and U. S. Navy bases, proving grounds, training centers, and other stations in the United States. At these bases the possible tactical uses of radar equipment were first explored, operating procedures for employment were worked out, problems of installation and maintenance were met, and the training of operators and maintenance personnel went forward. The work of MIT-RL personnel at these bases, though not spectacular, had an important bearing on the effective introduction of radar equipment into combat.

The field service outside of the United States constituted an extraordinary activity. It began in late 1942 with a small expedition to the Panama Canal Zone which took along special equipment to improve the air defense coverage of that vital area. It ended on V-J Day with a large group of MIT-RL personnel scattered throughout the Pacific, working intensely on the radar problems connected with the plans for the final assault on Japan. During the intervening three years hundreds of MIT-RL members journeyed to practically every theater of operation and to many remote bases to assist in introduction, installation, modification, and use of new radar equipment.

Although the greatest organized effort was represented by BBRL, extremely effective and, in many ways, more exciting work was accomplished by individuals or small teams who journeyed to remote locations on special missions. The adventures of the laboratory representative who supervised the installation and initial operation of the first Loran stations along the wild coast of Newfoundland and Greenland make an unequaled adventure story. The account of the representative who roamed the Pacific, visiting every base where the SCR-584 was in use, who followed a 584 ashore on Luzon a few hours after the first troops went in, and whose efforts put the 584 on the map as an operating instrument throughout the Pacific area, is another tale of high adventure and accomplishment. Others went into India and China to introduce Loran and radar equipment which greatly assisted in reducing huge losses suffered in operating over the "Hump."

In the summer of 1943, discussions between the British and American representatives on the

occasion of the Compton Radar Mission to England resulted in the proposal that MIT-RL representatives be sent to England to collaborate with the British in developing an improved type of navigational bombing equipment which the RAF needed and which the growing U. S. Air Forces would probably need. This was the beginning of the British Branch of the Radiation Laboratory, which occupied quarters supplied by the Telecommunications Research Establishment located in Great Malvern, Worcestershire. This initial cooperative effort resulted in the development of the so-called microwave "Oboe" system, which was widely used by the RAF and the U. S. Ninth Air Force. In the fall of 1943 the first radar bombing equipments for the use of the Eighth Air Force were sent to England, accompanied by MIT-RL experts, who were also attached to the British Branch. From that time on the projects undertaken by the BBRL rapidly multiplied. Many of them had to do with collaboration with the British, but as time went on the major problems were those concerned with assisting the U. S. Air Forces.

By the spring of 1944 BBRL had grown to such a size and its activities had become so widespread that it was felt desirable to establish a more intimate tie between it and the U. S. Army Air Forces. In collaboration with the expert consultant to the Secretary of War, Dr. E. L. Bowles, a civilian staff section, known as the advisory specialist group, was organized under General Spaatz, Commanding General of the U. S. Strategic Air Forces in Europe [USSTAF]. A member of MIT-RL was appointed a member of this staff, which served as an official liaison between the Air Forces and the civilian laboratories. The British Branch of the Radio Research Laboratory, known as ABL-15, was set up in a similar way.

This arrangement enormously improved the effectiveness of collaboration between the U. S. Forces and the civilian scientists since it gave the scientists a quasi-official status in the various Army commands.

BBRL took an intimate and effective part in assisting in planning, and in providing radar equipment for the invasion of France. Equipment on hand was modified, new parts and attachments for existing equipment and whole new equipments were sent quickly from the U. S. in order to provide the invading forces with the best possible radar equipment. BBRL experts followed the equipment into France, and after the fall of Paris, they set up an advanced service base in that city. The laboratory at Great Malvern still served as the main headquarters, and the development and test of new equipment and attachments was carried on there. The advanced service base, however, served as the headquarters for those operating with advanced air bases. With the assistance of BBRL personnel radar aids for tactical air operations were developed by the Ninth Air Force and its various tactical air commands in such a way that entire new operational procedures for carrying on tactical air operations, particularly at night and in bad weather, were evolved. Ninth Air Force Commanders have stated that the effectiveness of their units was doubled by the help of civilian experts, who worked with them on radar and tactical problems.

The enormous problem of introducing blind bombing into strategic air operations in the Eighth Air Force required continual assistance and attention from BBRL experts. The initial equipments, as always, were adequate for the solution of the problem, and improvements, modifications, and the introduction of new techniques went forward week by week. As large numbers of production bombing equipments arrived, many maintenance and repair bases had to be established, test and maintenance procedures set up, test and training equipment designed and put into operation. A group from BBRL was sent to Italy to assist the Fifteenth Air Force in similar problems, as well as to work with the Tactical Air Forces in the Italian Theater.

The efforts of civilian scientists, working closely with field commanders, were enormously appreciated by all the units with which they worked. All felt that having close at hand the advice of technical experts was invaluable in introducing new equipments. New equipment affects tactics, and changes of tactics affect the requirements of the equipment. Only through intimate back-and-forth discussions on the spot could the changing requirements of war be kept up with and could new equipment be adapted to the problem at hand. Even standard

equipments in large production and use were frequently adapted to new uses or modified to meet new tactical situations. The experience of BBRL and of other similar scientific groups in the war theaters has, it is believed, proved conclusively that in a technical war civilian scientists must play an important role not only in the laboratory but at the battlefront.

In May 1944, following a visit of Dr. K. T. Compton to the Pacific Theater, two units were set up in that area. The first was a small research group to collaborate with scientists of the Radiophysics Laboratory at Sydney, Australia, on problems of importance to Australian and U. S. forces in that area. This group helped introduce the latest microwave techniques to the Australian laboratory and assisted in the design of new equipment required in that theater. As the front moved away from Australia, this group became isolated, however, and was withdrawn. A second group was set up under OSRD auspices in Pearl Harbor, to operate with the Army Command in that area. This group assisted in radar matters with units of the Army which were staged in the Pearl Harbor area for forward operations. It also collaborated with the Navy in introducing new radar techniques, particularly for amphibious operations.

In early 1945 a Pacific Branch [PB] of OSRD was established in Manila, with a large radar section. An advisory specialist group, set up in the headquarters of the Far Eastern Air Force, served to tie the radar team into the Air Force Command. The radar group of PB-OSRD engaged at once in assisting with plans for the invasion of Japan. Extensive work in introducing radar aids for this operation and in training for the use of them was well under way when the end of the war suddenly came. A small and less formally organized group was attached to the Twentieth Air Force.

It is of greatest importance to recognize that the effectiveness of all the field service groups depended not only on the ability, skill, and adaptability of the men who went to the field, but to an even greater extent upon the support which the field group received from the home laboratory. The group in the field was only a forward branch of a strong, active development group at home. Problems are solved in the field only partly by making suggestions or revising equipment on the spot. To a much greater extent they are solved by the introduction of new pieces of equipment, either attachments or modifications of equipment in the field, or completely new equipments supplied quickly from the home base. In this way the field group could not only propose solutions to problems, but could provide within a short time the necessary equipment to accomplish the solution. It is estimated that for each man in the field from three to five men at the home laboratory were occupied on the average in designing, building, and shipping equipments called for from the field, in supplying information, and in working with Service agencies and manufacturers in the United States, in modifying production equipment, altering training procedures or equipment, and many other things.

Actually, of course, one did not set aside a specific three or four hundred men at the home laboratory to support the work of one hundred men in the field. Rather, the one hundred men in the field could call upon the talents and abilities of any one or a number of three thousand men and women at the home laboratory. These three thousand supplied a host of special techniques and skills and expert knowledge in all possible fields. Hence the group in the forward area could be sure that each of their problems could be handled by some specialized group at the laboratory. Furthermore, for rush jobs a very large "task force" could be assembled at the laboratory and thrown into the job of rushing specially built equipment to the forward area. Actually, therefore, each man at the front had behind him thirty men at home, not all of whom he used all the time, but upon any one or more of whom he could call for specialized help. In short, the field laboratory group was only as strong, but was fully as strong, as the group at home.

The impact of the field service groups was felt not only directly at the battlefront, but in every aspect of the activities in the zone of the interior. New experiences in the field were translated quickly into the design of new equipment, into alterations in factory production lines, and even in Army and Navy training and procurement policy. Often the fastest, the most complete and most useful information concerning field conditions as it affected radar equipment came via the

civilian channels. The weekly teletype conferences with the field groups were read as avidly in the Pentagon Building as in MIT-RL.

For these reasons, an important aspect of the effectiveness of a field service group was the adequacy of its communications with the home base. The main tie-line between all of the major field units in Europe and the Pacific and the home laboratory was a weekly teletype conference. This conference would last from one to three hours, and during it a large amount of information could be passed both ways, problems could be discussed back and forth on the spot, and solutions agreed upon. Supplementing the teletype, adequate and fast cable service was also essential for quick day-by-day messages; and finally it was essential not only to have channels for the communication of information, but for the transportation on rapid schedules, with high priority, of personnel and equipment. In some cases it was possible to have equipment arrive in the field within less than a week of the time it had been requested by cable or teletype.

Obviously this rapid communication and shipment system was clearly "out of channels" as far as the Army was concerned. Yet its vast usefulness was recognized by the Army itself, which provided most of the facilities employed. Many of the activities by the civilians in the field were equally out of channels from the Army point of view. The value of this too was recognized, and, indeed, the civilian method of operation was encouraged. On technical matters the formal channel, through Service Command, is often not suitable, important though such formal channels undoubtedly are in operational matters. The civilians, of course, had to learn to coordinate their efforts through various cognizant Army agencies and officers, and where this was not done confusion sometimes resulted. But this was a small price to pay for the fast-acting, effective assistance which civilian field groups were able to render.

1.14 PERSONNEL

An organization of any type, and especially a research and development organization, is no stronger than the men and women of whom it is composed. In this respect MIT-RL was exceedingly fortunate. In the early days of 1940 and 1941 it was able to attract to its ranks some of the outstanding and most active young physicists and engineers in the country. The accomplishments of MIT-RL are a tribute to the intelligence, the skill, the energy, and the enthusiasm of this great group of men. Probably never before in history had such a large, able group of physicists been assembled on a single project. This record was probably surpassed by the Los Alamos Laboratory of the Manhattan District engineers, but a number of the key individuals in that laboratory were acquired by transfer from the original MIT-RL group. The problem of microwave radar was undoubtedly ripe for the picking, but only a keen, active, and enthusiastic group could have plucked its fruits so effectively.

The keenest group of minds working individually, however, could never have accomplished what MIT-RL accomplished. Equally important was the congenial spirit of cooperation which permeated the entire laboratory from its first day until its last. Large as the laboratory eventually became, it always acted as one great family. The problems of one part or one group were the problems of all. Each individual member was willing and eager to do the tasks assigned and to work with whatever other individuals could be of help. No one can analyze how this spirit grew up and was maintained. It came not as the result of a conscious effort, but by a mutual desire which seemed to be conveyed quickly to each new recruit. But there are many things which contributed to keeping this spirit alive. The following are a few of these things.

1. The laboratory had only one purpose – to help win the war. It was organized at a time of impending danger and had its rapid growth during a time of great national peril. A deep, but usually unexpressed, patriotic motive actuated each individual.

2. The scientific and military problems on which MIT-RL worked were challenging and fascinating ones and all MIT-RL members felt they were making a real contribution to the war.

3. The laboratory was a temporary organization. It had no future career; its individuals

could have no long-term personal ambitions. Its job was to do its part in time of crisis and then to disband. It was organized from nothing, and therefore inherited no dead wood, no preconceived ideas, no red tape, no rigid organization. It was building for the present and not for the far future, and flexibility and rapid accomplishment were its main objectives.

4. Fixed and rigid procedures were avoided as far as possible, although some became inevitable as the organization grew large. In all cases, however, individuals felt that they could accomplish their task quickly and effectively with a minimum of interference and red tape. Great freedom was left to the individual, but great responsibility was placed upon him. All but a small minority met this challenge. Each division head, group leader, section head, or project engineer was given full responsibility for his task, accompanied by full authority to take whatever steps were necessary to accomplish it. Effectiveness was the goal, rather than efficiency, but in a larger sense, a greater efficiency was thereby achieved.

5. Salary scales were fairly and impartially determined. No specific salary was ever attached to any specific position or responsibility in the laboratory. Hence a change of responsibility or authority could be quickly made without raising complex questions of salary adjustments. Rather, salaries and wages were determined on the basis of experience of the individual, of his overall value to the laboratory as judged by those most closely associated with him, and, in the case of those who came on leave from permanent positions, by the salary received at the previous position. Positions of greater responsibility were aspired to by members of the laboratory only because this was a recognition of their ability and value and not because they carried a larger salary. The financial problem was thus removed from consideration in assigning tasks and responsibilities or in changing assignments as the program of the laboratory required or as the achievements and abilities of the individuals suggested.

6. A strong, active personnel organization, with the welfare of the individuals in the laboratory its only objective, supervised and administered all matters of personnel policy. A thousand-and-one minor matters, involving not only salaries but traveling and moving expenses and working conditions within the laboratory, were taken care of by Dr. F. W. Loomis, as associate director of personnel, with a foresight, ability, imagination, and keen interest in the welfare of each individual which won for him and for his organization the respect and admiration of the entire laboratory. No other factor contributed as much to the spirit and enthusiasm of the laboratory as this effective administration of personnel matters. To each and every employee MIT-RL was "a fine place to work."

Finally, and above all, it should be emphasized that MIT-RL was fortunate in acquiring a fine group of leaders. It was particularly fortunate in the men who headed its major groups and divisions. Many of these groups and divisions were very large organizations by themselves. The problem of operating them was difficult and the responsibility heavy. On the one hand leaders seemed to develop, as the need for them arose; on the other hand the organization of the divisions and groups was built around the key individuals who were available. MIT-RL never adhered to a rigid organization chart based on so-called logic or preconceived function; rather, the organization was built around the individuals available. The number of divisions, for example, was determined as much by the number of men of division head caliber as by the number of logical compartments into which the work could have been divided. If any particularly obvious "principle of organization" was adopted by the laboratory, this was it. A new section, a new group, a new project, a new division was created only when there was an obvious leader to head it. Frequently when key individuals were called away from the laboratory, or were transferred to other activities, the group or division they left, if there was no obvious successor, was reorganized to fit the capacities and abilities of those leaders who remained behind. Whether or not such a policy is suitable for other types of organization, for one devoted to research and development where the insight and imagination of individuals is the entire basis of success, this organizational policy seems to work.

1.15 CONCLUSION

This story (it is not a report) of MIT-RL covers only a few of the highlights of the work and achievements of a great organization. Apologies are due to the many men whose efforts and success made the laboratory what it was but who are not specifically mentioned in this paper. Every member of the steering committee, every group leader, every staff member and employee shares the credit for what was done. It is unfortunate that this story so inadequately covers the tremendous work accomplished.

Chapter 2

THE ORIGIN OF MICROWAVE RADAR AND LORAN NAVIGATION DEVELOPMENTS IN THE NDRC

2.1 INTRODUCTION

ONE OF THE LARGEST and most active divisions of the National Defense Research Committee [NDRC], Division 14, has been almost wholly concerned with developing improved radar equipment for the Armed Services in cooperation with American industry, the development laboratories of the Army and Navy, and our British allies. Although the scientists of NDRC entered the field only a year before Pearl Harbor, they have participated in the development of very nearly half the $3,000,000,000 worth of radar and associated equipment delivered to the Armed Services by July 1945. Their activity ranged from fundamental research on the behavior of super-high-frequency waves (microwaves), through the development of new vacuum tubes, new circuits, and new radar components, to the design of complete radar systems serving widely differing military purposes. In cases where a small number of units were urgently required by the Services these have been manufactured with the utmost speed by NDRC facilities. Finally, the work of the division has included, in many instances, an important share in the introduction of this new equipment into operational use in the field.

Distribution of Development Projects

The radar research and development of Division 14 was mainly concentrated in a single large secret laboratory, the Radiation Laboratory [RL], created by virtue of a contract with the Massachusetts Institute of Technology [MIT]. A number of smaller contracts were placed with other educational institutions, chief among them being Columbia University, and with industrial concerns supplementing the work of MIT-RL in a wide variety of component research and systems development and engineering activities. During World War II the number of NDRC contracts has averaged about 50.[a] The manufacturing facilities of industry were relied upon for all full-scale production under Army and Navy contract; but Division 14 had its own model shop, the Research Construction Company, Inc. [RCC] in Cambridge, Massachusetts, which worked in close cooperation with MIT-RL and shared with it the burden of manufacture under crash programs. By the end of August 1945, approximately $25,000,000 worth of radar equipment had been directly supplied to the Services by RCC and MIT-RL, slightly less than half of which had been produced by RCC.

[a] See complete list of OSRD contracts for Division 14, NDRC at back of volume.

Scope of Research and Development

Approximately 150 distinct radar systems were developed as a result of this research program, for use on land, at sea, and in the air, and for purposes ranging from early warning against enemy aircraft to blind bombing and antiaircraft fire control. The only section of MIT-RL not devoted to radar was responsible for the development of Loran, a pulsed long-range navigational aid widely used by the Armed Forces of America and Great Britain. A total of $71,000,000 worth of Loran equipment, all but one item of which had been developed in whole or in part by MIT-RL, was purchased by the Army and Navy by the end of July 1945.

The field activities of MIT-RL personnel took them to all principal theaters of war, to the European and Mediterranean fighting fronts, the China-Burma-India Theater and the South Pacific. A British Branch of the Radiation Laboratory [BBRL], a small group in Australia, one at the Mediterranean Allied Air Forces headquarters at Caserta, and an advanced service base in Paris backed up the efforts of the field representatives and drew in turn upon the resources of MIT-RL. When the war ended, some twenty-five MIT-RL men were in the Pacific or en route, while many others were standing by to man the radar laboratory it was planned to establish in Manila.

At the end of the war, nearly 5,000 persons

were engaged in radar development under Division 14 contracts, and of these over 3,900 were employees of MIT-RL. The nucleus of nearly a thousand scientists at this laboratory was drawn from universities and colleges in all parts of the country.

During the year 1944-45 the NDRC was allocating over $4,000,000 each month to Division 14 and the division received total allocations of $141,000,000 for the development of radar and Loran equipment since November 1940. When the amount spent on research and development is weighed against the dollar value of equipment actually delivered by July 1945, the sums invested seem relatively modest. Every dollar spent for research and development has produced a little over ten dollars worth of military equipment.

This statistical picture can convey some notion of the vastness of the enterprise, but it can give only an imperfect idea of its military contributions. The importance of the NDRC program to the allied war effort lies as much in the character of the new developments as in their magnitude. It is the successful development of radar using microwaves (i.e., radio waves only 10 cm in length or shorter) that distinguishes most sharply the NDRC development program from that of the Army and Navy laboratories. Although developed and perfected after 1940, microwave radar has seen extensive operational use and is largely responsible for making modern radar equipment as versatile and flexible a weapon as it became in the course of World War II.

The reasons underlying the importance of the development of radar systems employing microwaves has been discussed in Section 1.7. There it was pointed out that while range accuracy is not affected, the narrow beam made possible by such wavelengths greatly improves the accuracy of bearing location, the effective power, and the low coverage of the set and further makes more difficult the jamming of the set by enemy action.

2.2 RADAR BEFORE 1940

The early history of allied radar development has been briefly sketched in the release of the Joint Board on Scientific Information Policy and the nearly simultaneous release by the British Information Services. The story need not be repeated here. It is only proposed in this section to give a summary account of the state of radar development in the United States and England at the time of NDRC's entry into the field in the summer of 1940.

Viewed in retrospect, with the advantages of hindsight, the amount of engineering effort put on the radar program in the United States before the war seems woefully small for a nation of this size. Although work on pulse radar had been begun somewhat over five years before, it is doubtful if as many as two dozen persons were engaged full time on pulse radar research at the time of the outbreak of the European war in September 1939.

Early British Developments

The British had moved much faster, partly because of their greater proximity to the threatening danger. Under the encouraging wing of a highly placed advisory committee capable of assuring ample funds, radar research went forward rapidly between 1935 and 1940 in Admiralty and Army laboratories, and with marked success. The work originated in a specially created Air Ministry laboratory staffed by civilian physicists and engineers freshly recruited from the universities and industrial concerns. In September 1939 this laboratory numbered 200 to 300 persons.

Early U. S. Developments

Six months after the outbreak of war in Europe, when the Wehrmacht startled the world by crashing through the Low Countries, the American radar effort still was barely under way. In May 1940, the Navy received its first production unit of the historic CXAM, the earliest radar designed by the Naval Research Laboratory [NRL]. No production contracts for Army radar were let until August 1940. Although the Signal Corps laboratories had designed two excellent radar systems, prototypes of the SCR-268 and the SCR-270, production versions of these systems did not appear until early in 1941. Neither the Army nor the Navy had seriously undertaken the development of an airborne radar system.

The Navy's CXAM, the now obsolete patriarch of American radar systems, was an aircraft warning set for larger naval vessels. The Army's

first search sets, the SCR-270 and its successor the SCR-271, were land installations designed to give long-range detection and early warning against aircraft. The SCR-270 was a mobile installation transported by four trucks and a trailer, while the SCR-271 was a permanent installation with an operating building and the antenna on top of a fixed tower. The SCR-268 was a mobile set designed for searchlight and antiaircraft fire control.

From the present-day point of view these systems represent an early stage of the art. The defects that are mentioned at this point are inherent in the wavelengths that were the only practical choices at the time the sets were designed. It should not be forgotten that these sets were the only ones with which the Armed Services were provided at the time of Pearl Harbor. They continued to perform notable services to the last day of the war, often in conjunction with microwave equipment and often (such are the vagaries of procurement and logistics) in areas where microwave equipment had not penetrated.

All these early sets operated at frequencies of 200 mc per sec or below (wavelengths of $1\frac{1}{2}$ m or longer) and were provided with stacked array antenna systems giving at best about a 10-degree beam. The accuracy of bearing determination of the search systems was only about 3 or 4 degrees, but the sets gave excellent range. They gave no low coverage, provided poor target discrimination, and proved easy to jam. The CXAM had no height-finding features and the SCR-270 and 271 could only estimate the height of approaching aircraft by making use of the known pattern of the multiple-lobe beam produced by the ground reflections. This required careful calibration of the pattern at the chosen site and gave only approximate results.

Since the SCR-268 was designed as a precision pointing set, its maximum range is only 25 miles. It is beset by siting problems and difficulties from ground reflections, and during the war its utility was seriously impaired by enemy jamming. A higher degree of accuracy than was inherent in its 10-degree beam was attained in the measurement of azimuth and elevation by means of a technique called lobe switching using a divided beam. A positioning accuracy of about 1 degree was possible by this method.

Problems of Designs in Field Use

By June 1940, the British had made great strides. The center of radar activity was the Air Ministry Research Establishment [AMRE] which had just moved to a site near Swanage on the south coast of England, and had grown to be a large affair. The development of radar systems was also going forward at the Army's Air Defense Research and Development Establishment [ADRDE] at Christchurch, at the Admiralty Signals Establishment at Portsmouth [ASE], and at the Royal Aircraft Establishment [RAE] at Farnborough.

Besides the east coast chain of early-warning [CH] stations, which were already in service but had not yet been seriously called upon in the defense of Britain, the British had several other systems in use and still more in development or production. A small number of mobile units had been sent to France with the British Expeditionary Force in the fall of 1939. The British ground systems, all of which operated on frequencies below 200 mc, had the same defects enumerated in the case of American equipment.

Of major importance, because this experience became the basis of the work of NDRC, were the pioneer efforts of the British in the field of airborne radar. This was of two main types: *aircraft interception* [AI], equipment for night-fighting aircraft; and *aircraft-to-surface-vessel* [ASV] equipment for the detection from the air of ships and surfaced submarines. Primitive versions, hardly better than experimental, of both types of equipment were introduced into Service use somewhat prematurely during the fall and winter of 1939-40. No operational successes are unequivocally on record for either type of set. Improved versions of both types, thoroughly engineered and well designed, were just reaching completion in June 1940 and were introduced into operational use in the autumn of 1940.

These two historic pieces of equipment, known as ASV Mark II and AI Mark IV, both appeared in time to exert a telling effect upon the enemy. The ASV Mark II was used with great success by the Coastal Command of the RAF in the North Sea, the Channel, and the Bay of Biscay against German submarines which began to operate from their newly acquired French bases in the

fall of 1940. Just as the CH stations played an historic role in repelling the daylight bombing during the first phase of the Battle of Britain in the fall of 1940, so the AI Mark IV installed in the powerful and well-armed Beaufighter aircraft and guided to the enemy attackers by specially designed *ground control of interception* [GCI] equipment helped to defeat the Luftwaffe during the winter and spring of 1941.

Both these sets operated at approximately 200 mc and had beams of exceedingly low directivity. This lack of directivity was a particularly serious defect in the case of the AI Mark IV, even though it was partially remedied for purposes of accurate positioning by the use of lobe-switching techniques. The difficulty came from ground reflections which, when the plane flew below a certain height, blanked out all echoes coming from horizontal distances greater than the plane's altitude above ground. To realize the full range of the set, it was necessary to fly high enough so that the transmitted energy did not strike the ground. Because of the breadth of the beam, this was sufficiently high to give the enemy the opportunity of coming in low, beneath the operating altitude of the nightfighters. Although the enemy never fully exploited this possibility, and did not hit on it until it was too late, the threat was ever-present.

These defects of the AI Mark IV led the British to consider, even before the outbreak of war, the possibility of going to shorter wavelengths (higher frequencies) capable of producing really narrow beams. By the early fall of 1939 the British launched two programs, one shorter-range and one more ambitious, to achieve these results. The shorter-range program was directed toward the development of 50-cm equipment using greatly perfected, but essentially conventional, techniques. The second program was to develop what hitherto did not exist; a powerful source of radio-frequency energy in the neighborhood of 3,000 mc (10 cm).

The British had an experimental 50-cm system in operation early in 1940. At the time when an improved version of this system was about to be tested, in the late spring of 1940, the whole program was cast into the shade by the dramatic success of the longer-range program. As a result of a brilliantly conceived and swiftly executed research program, workers at Birmingham University, in cooperation with British industry, had successfully designed and brought into production a tube capable of giving several kilowatts of peak power at 3,000 mc. This new type of vacuum tube, the resonant cavity magnetron, was strikingly different in form and principle from any previous type of tube. By opening up the hitherto unexplored field of microwaves, the magnetron may well have caused the greatest single revolution in the field of radio since Lee De Forest's invention of the three-element vacuum tube.

2.3 EARLY HISTORY OF MICROWAVES

Microwaves have been known from the earliest days of radio, but until the development of the cavity magnetron by the British they were hardly more than scientific curiosities. They could not be produced by ordinary means. Conventional triode vacuum tubes can be used over a wide range of the radio spectrum but only by pushing refinements close to the limit can they be used to generate waves shorter than 50 cm. Special techniques have to be employed to generate, transmit, and receive microwaves. Before 1940 the principal sources of centimeter waves were: (1) spark-gap transmitters, (2) Barkhausen-Kurz oscillators, (3) the klystron, and (4) the split-anode magnetron, the ancestor of the device developed by the British. In the years just before the war only the last two devices appeared to offer possibilities of operating efficiently at 10 cm or below.

The Klystron. The klystron was developed by workers at Stanford University and its existence was first made public in 1939. The tube, which has been many times described, is of the so-called velocity-modulated variety and involves the first important application of resonant cavities to vacuum tube construction. The first tubes operated in the neighborhood of 12 cm and gave about a watt of power.

The Split-Anode Magnetron. A much more promising tube for the very highest frequencies was the so-called split-anode magnetron. This was derived from a simple, magnetically operated two-element vacuum tube first described in 1921 by A. W. Hull of the General Electric Com-

pany. This tube had very poor efficiency even for the generation of comparatively low frequencies. Shortly afterward it was discovered in Germany that dividing the cylindrical anode into two half-cylinders improved the tube as a generator of relatively long waves. But it was a Japanese worker, Kinjiro Okabe, who was chiefly responsible for demonstrating that the split-anode structure could turn the primitive magnetron into a useful (for experimental purposes) generator of ultra-high-frequency and hyperfrequency waves.

Much work was done in all parts of the world in the decade following Okabe's first papers in 1927 to improve the magnetron. By increasing the number of anode segments, by careful attention to methods of cooling the tube, and especially by trying to improve the associated circuit (some of the best work in this direction was done in American industrial laboratories) such progress was made in this type of tube that in 1939 it was reported by E. G. Linder of the Radio Corporation of America [RCA] that an output of 20 w could be obtained at 8 cm with an efficiency of 22 per cent.

Cavity Magnetron. When in England Professor Oliphant and his associates, Randall and Boot, began the search for a high-power source of hyperfrequency waves, they undertook two parallel lines of attack to improve the klystron and to improve the magnetron. What proved to be the successful solution bore to some extent the mark of both approaches, for it consisted in abandoning the split-anode construction in the magnetron and introducing a high-efficiency circuit in the form of associated resonant cavities. By June 1940 with the collaboration of the British General Electric Company they had developed a manufacturable tube giving 10 kw of peak power on pulses of 10-cm energy. The order of magnitude of this improvement was such as to constitute a major revolution in the radio art.

Waveguides. Even before the development of the cavity magnetron some important pioneering work had been done in the United States on the properties of microwaves using the low-power sources then available, and some attempt had also been made to use them for detection purposes. The quasi-optical behavior of damped centimeter and even millimeter waves had of course been carefully studied by Righi, Lebedew and others among Hertz's immediate followers. But the study of the transmission and reception of centimeter waves may be said to have been launched in 1936, the year when G. C. Southworth of the Bell Telephone Laboratories [BTL] and W. L. Barrow of MIT first reported their independent discoveries that microwaves can be conducted down hollow pipes, as well as by means of coaxial cables, and that they could be projected into space or picked up by means of horns made by flaring the ends of such waveguides.

In the same year W. W. Hansen at Stanford began his important work on properties of resonant cavities. Research on microwaves continued uninterruptedly at the Bell Laboratories, Massachusetts Institute of Technology, and Stanford, until the war. Fundamental research at MIT centered on the properties of waveguides and horns and on the characteristics of dielectric materials; at Stanford it was chiefly devoted to the development of the klystron and the theory of resonant cavities; at BTL it soon included important work on crystal mixers and other phases of the receiver problem.

Continuous-Wave Applications. A number of independent attempts were made in the decade before the war to use microwaves for detection purposes. The Signal Corps Laboratories, and to lesser extent the Naval Research Laboratory [NRL], experimented with c-w (continuous wave) methods of detection with microwaves before putting their full effort on longer-wave pulse radar. The RCA-Victor Division of RCA experimented with c-w detection in cooperation with the Army and later had some success with a pulse detection system on 3,000 mc. In 1936 the General Electric Laboratories [GE] published an account of successful detection of objects with microwaves by means of the doppler effect using c-w radiation. Similar experiments were made in Germany and in France. The French had a microwave set on the *Normandie* as an obstacle detector. The low-power split-anode magnetron was the source of radiation in nearly all these cases and the ranges obtained were prohibitively short.

In America most of these microwave detection efforts had either been abandoned or severely curtailed by 1940. However, an active program

of aircraft detection using the klystron as the source of c-w radiation was in progress at San Carlos, California. This was a joint project of the Stanford Physics Department and the Sperry Gyroscope Company. Similar work was started shortly thereafter in the Department of Electrical Engineering of MIT. Here the communications division under Professor E. L. Bowles had been experimenting with a radio blind-landing project using ultra-high-frequency techniques as developed by Barrow and his co-workers. Early in 1939 a straight-line glide-path scheme was tried using the klystron as the source of 40-cm waves. Later in 1939, the MIT group entered into an agreement to conduct a research program, under the sponsorship of the Sperry Gyroscope Company, pointing to the development of an aircraft detecting device on 10 cm using the klystron. A crude c-w detection device using three horns (one transmitting horn and two receiving horns) was set up on a movable platform mounted on a Sperry searchlight base.

Early in 1939 Alfred L. Loomis, New York lawyer and scientist, began work at his private Tuxedo Park laboratory on the general field of ultra-high-frequency work using the klystron, and later in the year contributed funds to support a program of microwave propagation research at MIT. In the spring of 1940, Loomis made arrangements with E. L. Bowles for a program of microwave detection at Tuxedo Park in cooperation with the MIT group. An experimental set using an 8.6-cm klystron as the transmitting source to detect objects by the doppler effect using c-w radiation was built during the summer of 1940 by Loomis and his co-workers.

2.4 THE INAUGURATION OF THE NDRC RADAR PROGRAM

It was clear from the time the first plans were made in June 1940 for a civilian war weapons program that NDRC should concern itself with some phase of radio detection. The earliest proposals provided that a section of K. T. Compton's Division D should be devoted to detection, broadly conceived, including work on searchlights, acoustical detection, infrared and microwaves. The decision to limit the detection work to the field of microwaves was made almost at once.

Since there was as yet no knowledge of the British magnetron, such a decision fulfilled to a fault the condition that the civilians should concentrate on long-range projects deemed too speculative for the Service laboratories in time of war. Furthermore it was in harmony with the suggestions submitted to Vannevar Bush by the Armed Services late in June. These suggestions emphasized the importance of general studies of pulse transmission and reception and of basic research in the hyper-frequency field. The Air Corps, the suggestions revealed, was especially interested in certain problems of instrumentation (fog and haze penetration and the possibilities of reconnaissance and bombing through the overcast) where the solutions undoubtedly lay in the ultra-high-frequency or hyper-frequency radio fields.

This decision resulted in a necessary and natural division of effort. It left the field of longer-wave radar in the hands of the Army and Navy personnel who had developed it, and who were deeply involved in improving it and shepherding it through production. Since all the detection experiments undertaken in civilian laboratories independently of the Armed Services had been in the field of microwaves, it put the civilians to work where they had already acquired some experience.

Executive Organization

The man selected by Compton to organize a section devoted to detection, Alfred L. Loomis, was one of the most energetic and enthusiastic of these microwave pioneers. Loomis had close personal and scientific connections with Bush and Compton. He was a trustee of MIT and of the Carnegie Institution. He had generously contributed from his own pocket to the support of microwave research in the Department of Electrical Engineering at MIT; and as we have just mentioned he was at this time conducting some microwave experiments, in cooperation with the MIT group, at his own laboratory at Tuxedo Park. Bush and Compton were following this work closely.

Loomis chose as his first associates on what came to be called Section D-1 of NDRC, or the Microwave Committee, Ralph Bowen, director of radio and television research at BTL, and two

other men who had experience with the microwave field: E. L. Bowles of MIT, who became secretary of the committee, and Hugh H. Willis, research Director of the Sperry Gyroscope Company. These four men held their first meeting on July 14, 1940. During the next few months the following persons were added to the committee: R. R. Beal, Director of Research of RCA; George F. Metcalf of the General Electric Company [GE]; J. A. Hutcheson of the Westinghouse Electric and Manufacturing Company; and Ernest O. Lawrence, professor of physics and director of the radiation laboratory for nuclear physics at the University of California at Berkeley. It was a group experienced in the administration of scientific research, well versed in current radio developments, well placed to coordinate the scattered work in this new field, and well fitted to administer the funds soon to be placed at its disposal.

Objectives

The committee defined its objectives in these terms: "So to organize and coordinate research, invention and development as to obtain the most effective military application of microwaves in the minimum time." The next two months were spent in learning what the Armed Services had accomplished in radio detection behind their veil of secrecy, and surveying the field of microwave research to determine what developments seemed most promising.

The survey revealed that much interesting work was in progress in various commercial and university laboratories, but that there was no sign that a vacuum tube was anywhere in production or development which might give adequate power on the very short wavelengths which the committee had decided would be most desirable, namely, 10 cm or below.

Only two vacuum tubes seemed to offer possibilities below one meter, the klystron, already being commercially developed by Sperry; and the so-called resnatron, a multi-element vacuum tube developed at the University of California. The possibilities of the latter tube were carefully investigated by the committee, and it was found capable of giving about a kilowatt of peak power at about 45 cm. There was reason to expect that the frequency and the power could both be raised by further development, although there was little promise that it would yield a source of energy at wavelengths as short as 10 cm. On the recommendation of the Microwave Committee, the NDRC let its first microwave contract on November 1, 1940, with the University of California for the development of a higher-power and higher-frequency resnatron.

2.5 THE BRITISH TECHNICAL MISSION

This was the rather uncertain prospect when the British Technical Mission, headed by Sir Henry Tizard, arrived in Washington and began conversations with the representatives of the U. S. Army and U. S. Navy early in September 1940. In these discussions each nation divulged to the other the details of its secret radar developments.

About the middle of September, the way was cleared to have the appropriate members of the Tizard Mission meet the section leaders of NDRC. By special arrangement, the Mission was empowered to treat with the civilian scientists on the same terms as with the Armed Services.

The first contact between the radar members of the Mission and representatives of NDRC took place at an informal evening conference held at the Wardman-Park Hotel late in September. The first extended talks took place over the weekend of September 28th when J. D. Cockcroft and E. G. Bowen, the radar specialists on the Mission, met with several members of the Microwave Committee and of NDRC as guests of Alfred Loomis at Tuxedo Park. It was on this occasion that the British explained their long-range objectives in radar (especially the importance to them of a microwave airborne set without the defects of the AI Mark IV) and showed the committee members the sample cavity magnetron they had brought with them as their prize exhibit.

U. S. Production of Magnetron

During the first week of October, the British representatives, with the official approval of the United States authorities, disclosed the cavity magnetron to engineers of BTL, the organization they had selected to manufacture it in this country. On Sunday, October 6, the tube was operated

for the first time in this country in the presence of Bell engineers and work on duplicating the device began the following day at BTL.

Meanwhile the disclosure of the magnetron had exerted a profound effect upon the members of NDRC and Section D-1. The new tube removed the chief obstacle to a successful development program in the microwave field. A major breach had suddenly been opened in the line through which the reserve strength of American university and industrial resources could pour. With energetic exploitation of this initial stroke of good fortune, microwave radar could be developed in time to be useful in the war. This was the article of faith, and it was not universally shared in all quarters, upon which the Microwave Committee with the prompt and active encouragement of Bush and Compton based their subsequent decisions.

During the first two weeks of October a series of important conferences was held in Cambridge, New York City, and Tuxedo Park in the course of which the main outlines of a concrete program were formulated by the Microwave Committee. E. G. Bowen, who was remaining behind after the departure of the Tizard mission, took an active part in these discussions, by describing the British Air Ministry's radar research organization, and by helping to lay down the specific objectives for a microwave program.

There was general agreement that a central laboratory under civilian direction should be set up at once, staffed, in the manner of Britain's AMRE, as much as possible by research physicists from the universities of the country. This policy had proved extremely successful in England. It was at first felt when the possibilities were canvassed that the laboratory should be set up at Bolling Field, Washington, D. C., where a large heated hangar with associated laboratories would be erected by the U. S. Army.

2.6 THE FIRST THREE PROJECTS OF THE MICROWAVE COMMITTEE

It was also decided, largely on the basis of British need, to concentrate on three projects, not greatly different from those proposed by the American Armed Forces. Two out of three were to use the cavity magnetron. Project I, and the project of greatest urgency from the British point of view, was to build a 10-cm AI system. Project II, also to be entrusted to the National Research Council of Canada, was to develop a precision gunlaying radar capable of great accuracy. Project III was to design a long-range navigation device, one in which the aircraft sent out no signals, but which, when a plane was over enemy territory some 500 miles away from its base, could tell the navigator his position within a quarter of a mile.

Definite steps were agreed upon to launch Project I. Bowen, who was England's outstanding authority on airborne radar, drew a block diagram of component parts necessary for a microwave AI system, and from his knowledge of the operational requirements, laid down the specifications the equipment should be designed to meet. For experimental purposes it was decided to ask the principal electronic and electrical concerns to design and supply a few units of each of these components. These proposals were officially agreed upon at an important full-dress meeting of the Microwave Committee held in Washington on October 18 and attended by Bush, Compton, and several high-ranking Army and Navy officers.

As a result of a last minute decision arrived at two days before, the Microwave Committee at this meeting unanimously approved plans to establish the microwave laboratory at MIT. Various factors entered into this decision. Some delays had been encountered in getting matters underway at Bolling Field, and what was doubtless more important, it was pointed out that the NDRC was not empowered to administer its own laboratories but should operate through contract with existing institutions. Work on microwaves being already in progress at MIT, the atmosphere should be a congenial one. When Compton arrived in Washington on October 17 he was confronted with the proposal, agreed upon in conference the previous day by Bush, Jewett, Loomis, and Bowles, that MIT offered a better prospect than Bolling Field. He was persuaded to give his approval and to telephone MIT to ascertain if the required space could readily be made available.

On October 25, 1940, the NDRC approved the program as submitted to it by the Microwave

Committee. This covered the five development contracts for the components and the contract with MIT which was later signed on February 5, 1941. The sum of $455,000 was allocated for the first year of the laboratory's existence.[b] How modest this appropriation was should be evident from that fact that it envisaged a laboratory of only fifty persons, including technical assistants, mechanics, and secretarial help.

2.7 FOUNDATION OF THE RADIATION LABORATORY

E. O. Lawrence had actively joined the work of the Microwave Committee early in October in response to an urgent summons from Bush. The importance of his addition to the committee was evident as soon as it was decided to draw mainly upon American academic physicists in finding personnel for the new laboratory. He alone, perhaps, of the members of the Microwave Committee could readily have enlisted the support of his colleagues in the American Physical Society in a project the details of which could not at first be disclosed. His first success, soon after his arrival in the East, was in inducing L. A. DuBridge, Chairman of the Physics Department and since 1938 Dean of the Faculty of Arts and Sciences of the University of Rochester, to accept the post proffered him, by the Microwave Committee and by Compton, as head of the microwave laboratory. Lawrence also made visits to colleagues at Harvard, Princeton and other Eastern institutions, while DuBridge went to the University of Indiana where a small group of physicists from several Midwestern universities were meeting in an interdepartmental seminar. These men were sounded out in general terms.

More active recruiting took place in Cambridge by Lawrence, DuBridge, and the Microwave Committee during the week of October 28-31 when a conference on applied nuclear physics brought to MIT some 600 physicists from all parts of the country. At the conclusion of the conference most of those who had been approached left Cambridge, but a small group remained behind, and strengthened by personnel chosen from Harvard and the Massachusetts Institute of Technology, began a general discussion of certain key microwave problems and took steps to occupy the space set aside for the new laboratory in the wing of the main MIT building occupied in part by the Department of Electrical Engineering.

On Monday, November 11, there was held the first general group meeting of the laboratory personnel. At this meeting, and one held the following day, attended by Alfred Loomis and E. O. Lawrence, the main outlines of the laboratory organization were agreed upon. Research problems were parceled out among seven technical sections concerned with developing or improving the chief components of the system. Section I was concerned with pulse modulators, Section II with transmitter tubes, Section III with antennas, Section IV with receivers, Section V with problems of microwave theory, Section VI with cathode-ray tubes, and Section VII with work on the klystron. A final section, Section VIII, the coordination section, was charged with the technical integration of equipment being manufactured or designed for the use of the laboratory.

By the middle of December the organization consisted of some 35 persons. About half of the promised space had already been occupied and a roof laboratory—a wooden penthouse covered with grey-green tarpaper—had been erected on the roof of MIT Building 6, and a second story was being added. The personnel consisted of about 30 physicists, three guards, two men in charge of the stockroom and the purchase of supplies, and one secretary. The laboratory was placed under the supervision of an executive committee consisting of Loomis and Bowles of the Microwave Committee, L. A. DuBridge, the director of the laboratory, and Melville Eastham, president of the General Radio Company, the business manager. It had already received the name of "Radiation Laboratory," selected because it concealed, yet in ironical fashion, expressed the functions of the laboratory. The adoption of the name used by Lawrence's cyclotron laboratory at Berkeley, suggested the natural hypothesis that this group of nuclear physicists was engaged in nuclear physics, then deemed a harmless and academic occupation.

BTL delivered their first five magnetrons precisely on schedule on November 18. The first units of the other components began to arrive

[b] Under the contract NDCrc-53.

shortly after. It was recognized from the beginning that these components were only a starting point. Work was coordinately begun on testing and adapting the delivered items, on design of new components suitable for use in an aircraft, and on assembling a first working microwave radar with the equipment available.

On the afternoon of December 16, a planning meeting was held at the laboratory and a schedule to be met was laid down. This provided that by January 6 a microwave system should be working on the roof; that by February 1 equipment should be working in a flying laboratory, a B-18 plane to be supplied by the Army; and that by March 1 a system should be working in an A-20-A aircraft, which at that time was the most likely choice for a nightfighter. A group charged with the assembly of the system was at once set up.

First Experimental System

During the last two weeks of December the first experimental radar system was assembled in the roof laboratory largely from the components supplied with such admirable dispatch by the commercial concerns. The system had a separate antenna for transmitting and for receiving, for the problem of a duplexer, or what the British referred to as a *transmit-receive* [TR] box, to permit the use of the same antenna for transmitting and receiving, had not yet been solved. This system was first successfully operated on January 4, 1941, two days ahead of schedule, and picked up echoes from the buildings of the Boston skyline across the Charles River.

Single Parabolic Antenna Trials.—In order to design a system for use in an aircraft, it was imperative that it operate with only a single antenna. Yet with a single parabola without a duplexing or switching device, or at least some protection for the receiver crystal, the main transmitted pulse would burn out the receiver crystal. While various solutions were being tried, it was discovered early in January that a klystron used as a preamplifier tube, would serve effectively as a buffer for the crystal. While only a partial solution to the TR box problem, it permitted the roof system to be operated with a single paraboloid on January 10. Before the end of the month an almost identical system with its components shock-mounted was operating in a wooden mock-up intended to represent the nose and front gunner's compartment of a B-18.

As yet, this system had only picked up ground echoes. Attempts to pick up aircraft signals had failed and some observers doubted that the system was capable of performing this essential feat. As a result of frantic efforts and some last-minute improvisation, aircraft signals were observed on February 7 in time to be reported by telephone to a gloomy session of the Microwave Committee which DuBridge was attending in Washington. The report of this success changed the mood of the meeting which voted confidence in the AI program.

Development of Airborne System

Between February 13 and March 5 the system that had been in the mock-up was worked over and modified for installation in the plane. On March 6-7 it was installed in a B-18 plane, equipped with a special Plexiglas nose transparent to hyperfrequency radiation, which had been flown up from Wright Field by an Army crew. The equipment was first flown on March 10. Its performance was steadily improved during the rest of the month.

On March 27 there took place a flight in the B-18 with several laboratory scientists aboard which had important consequences for the laboratory. The equipment performed admirably, and for what was probably the first time an airborne microwave radar was tried out for *aircraft-to-surface vessel* [ASV] purposes. Tests on a 10,000-ton ship gave strong signals, and the "sea return," i.e., interfering echoes from the surface of the water, was much less than had been feared. Encouraged by this success, the plane was flown to New London to look for submarines operating near that base. There the pilot made successful runs on a surfaced submarine and the men found that from an altitude of 500-1,000 feet strong signals were obtained at a distance of 3 miles.

The first flight of the experimental AI equipment on March 10 can be taken to mark the end of the first phase of the laboratory's history. On this date the Microwave Committee submitted its first report on the laboratory to Bush, describing the progress that had been made in the AI

development, upon which most of the Laboratory effort was concentrated, and the less extensive results of Project II, gunlaying, and Project III, long-range navigation, to be discussed in subsequent text.

Up to the month of March the main effort at MIT-RL had been to get a plane in the air with radar aboard, and to meet as closely as possible the schedule laid down in mid-December. This phase of the laboratory's history was now closed, and there began a period of greatly expanded and diversified effort. The laboratory's attention was still primarily directed toward a perfected AI equipment suitable for operational aircraft. This was predicated chiefly upon the successful design of new and improved components. But there was increased activity in Projects II and III and additional development along two main lines: (1) new applications of the 10-cm AI equipment, especially those involving the use of microwave radar over water, and (2) development of radically new types of radar.

PART II

PROGRAM OF RADIATION LABORATORY AND ASSOCIATES

SECRET

Chapter 3

TECHNICAL PROGRAM OF THE RADIATION LABORATORY

3.1 MICROWAVE RESEARCH

Unquestionably the most important aspect of the laboratory's effort during the first year, and almost equally vital in the years that followed, was the development of improved components and the steady growth of knowledge of the properties of microwaves: how to produce them, carry them along coaxial cables or waveguides, receive them, amplify them, and display them; how they are propagated through the atmosphere and how they behave under different meteorological conditions.

A word should be said about the manner of work. The laboratory was loosely and informally organized, small enough for constant interaction of the various parts, and even for frequent exchange of personnel. The spirit and morale were very high. The lines separating the different sections were anything but formal barriers. Men drifted across them freely, to aid one another in a tight spot, even sometimes to trespass to good effect in someone else's preserve. It was a picked group, fully conscious of its undiluted strength, as yet untroubled by problems of production and higher diplomacy, unencumbered by administrative routine.

These men shared with the industrial laboratories, chief among them the Bell Telephone Laboratories [BTL], the experience of laying the foundations of a new engineering art. The conditions and objectives of research were widely different from what most of the men had been accustomed to. It was applied science; and it was also wartime science. Especially during the first year the men relied upon empirical investigation of the cut-and-try variety, guided by their theoretical training and insight, but without benefit of much practical experience in radio engineering. The rediscovery, en route, of familiar engineering dodges was not an uncommon experience. They felt, on the other hand, that they were free from a heavy load of accumulated practices of radio engineering not always adaptable to this new field. The wartime urgency of their work meant that a wholly logical, planned attack on a problem as in peacetime, was almost never feasible. Speed was the all-important consideration and there was no time for leisurely theoretical exploration or fundamental research underlying a given problem. Most of the knowledge was acquired by building something as quickly as possible and trying it out. Theoretical knowledge grew *pari passu* to be plowed back into the work at a later date. Hence the importance of the various experimental systems soon scattered throughout the laboratory. Experimentation consisted mainly in trying out new components and new ideas as swiftly as possible in the experimental systems on the roof or in the B-18. A roof system group was established early in February for conducting such testing and for the general improvement of microwave system design.

3.2 DEVELOPMENT OF IMPROVED COMPONENTS

3.2.1 Experimental Systems

The first systems were frankly experimental, intended to educate the laboratory members in the new art, and to help them obtain some general familiarity with the properties of microwaves. All the earliest systems were assembled almost entirely from the components supplied by industrial concerns under the first contracts. These components in some instances had been considerably modified and changes in them were constantly being made. A rebuilt Westinghouse pulse modulator, a Bell copy of the British magnetron, a Sperry paraboloid and scanning gear, a receiver consisting of a BTL crystal mixer, a grounded-grid triode local oscillator, together with an RCA intermediate frequency amplifier; these found their way into all the early experimental systems. The only component in the early systems designed and built entirely by the laboratory was the very important synchronizer unit, of which about twenty were built by hand in the first few months. It was used to provide triggering pulse to the modulator, banking

pulses to the receiver, and to synchronize the sweep circuits for the cathode-ray tube.

Only the briefest outline is possible here of the complex activity which produced, within less than a year and a half, a satisfactory, if primitive, operative microwave radar system. Work began on the development of components during the first days of the laboratory.

3.2.2 Development of Components

Magnetron

The essential features of the 10-cm magnetron were not substantially altered. The development of power-measuring techniques and of spectrum analyzers made it possible to understand the potentialities of the tube and to get much more power out of it than the British had been led to expect. The introduction of a technique called "strapping," which the laboratory learned from the British in the fall of 1941, greatly increased the stability and the efficiency of the magnetron. Although no wholly satisfactory theory of magnetron operation was evolved, much was learned about the modes in which the tube can oscillate.

The most important achievement – and one upon which the magnetron group concentrated from the very first—was the development of a magnetron operating on 3 cm. This was successfully accomplished in the spring of 1941 with the adoption of some novel changes in magnetron design. In both the 10-cm and 3-cm work the laboratory was greatly aided by a vacuum-tube model shop facility provided by the Raytheon Manufacturing Company in Newton, Massachusetts. Here a handful of tube experts produced experimental magnetrons, modulator tubes, etc., following suggestions and drawings submitted by MIT-RL. Raytheon operated on a subcontract from MIT's Division of Industrial Cooperation, MIT being reimbursed under the OSRD prime contract OEMsr-5.

Pulse Modulator

The pulser or pulse modulator, supplied by Westinghouse and used in the early experimental systems produced pulses of the required length and repetition rate, but was too wasteful of space, weight, and power to be a satisfactory design. As early as November 8, 1940, the pulse-modulator problem was discussed with a view to developing a unit suitable for aircraft use. Two important developments of the modulator group during the winter of 1940-41 laid the foundations for the later art of radar pulse modulators. The first of these was the development of a "bootstrap" cathode-follower circuit. The second was the discovery of the pulse-forming network. These were important elements in the design of the so-called service modulator and laboratory modulator embodying these developments, both of which were manufactured during the year by Raytheon. The use of the network did much to improve the pulse shape and later became the basis of the high-power modulator using the pulse-forming line with rotary spark gaps.

An important contribution to the work of the modulator group was the development of testing equipment (r-f envelope viewers and synchroscopes) which permitted the study of pulse shapes. Special adaptations of the basic circuits were used in designing the modulators for various laboratory systems intended for production. Work was begun late in 1941 on the high power modulators and on the development of modulators using oxide-coated cathode output tubes, among them a light-weight pulse modulator manufactured by the Stromberg-Carlson Company, later referred to as the Navy standard pulser.

Antenna Design

Improvements in antenna design consisted largely in finding the proper way of feeding r-f energy to a standard parabolic reflector, and determining the optimum focal length and the proper design and proper matching of the radiating dipoles. The effort was concentrated upon getting a high-gain pencil beam with low side lobes, without introducing very novel reflector dish design.

R-F and I-F Problems in Receiver Design

Use of I-F. The receiver problem divided itself into the r-f and the i-f problems. The earliest i-f receiver strips from BTL and RCA had been designed on the basis of television experience and were only a first approximation of what was re-

quired for microwave radar. In its broad outlines, the development was conservative and there was no departure from the basic superheterodyne principle; yet there were fundamental departures in circuit design which made it possible to design high-gain and broad bandwidth receivers with proper transient response. The novel problem in radar was to build receivers that could tolerate unbounded signals and escape paralysis from the effects of the main transmitted impulse.

R-F Receiver-Detectors. The receiver r-f problem was part of the broader problem of handling r-f energy on these frequencies. The answer to the question as to which first detector, whether a crystal mixer or a grounded-grid triode was better, hinged in great part upon a solution of the duplexing or TR box problem. The earliest laboratory experimental systems used a crystal detector, then shifted over to the use of a BTL grounded-grid triode, and finally settled on the crystal mixers which became standard for all subsequent microwave radar. This was both because crystals had finally nosed out tube detectors in the race for sensitivity and because the solution of the TR box problem gave adequate protection to the crystal.

R-F Coaxial Lines and Test Equipment. The earliest r-f work at the laboratory, in connection with designing a 10-cm AI system, was centered on three main problems: to design improved coaxial lines and line components such as tuners and rotary joints; to evolve measuring equipment to test the components under development; and to solve the TR-box problem. The coaxial line was first radically improved by designing a beaded line using a particular nonuniform spacing of the polystyrene beads, and finally by adopting the use of brass stubs instead of beads to support the inner conductor. To meet the need of measuring equipment, standing-wave detectors, wavemeters and wattmeters were developed and improved. In the spring of 1941 the laboratory designed a successful and rugged spark-gap TR box which was followed by the adoption and improvement of the British so-called soft Sutton Tube TR. A further improvement in the duplexing system was the adoption of "preplumbing." This consisted in the preselection of th[illegible]oper length of transmission line between the magnetron and the TR box, so as to insure without special tuning devices, the minimum loss in received signal.

Adoption of Waveguide Transmission Lines. With the appearance of the first 3-cm magnetrons in the spring of 1941 the whole art had to be translated to this new wavelength. Waveguide transmission lines were adopted instead of coaxial lines, which would have to be prohibitively small. The properties of waveguides had to be carefully studied, and a complete new set of components, such as tuners, rotary joints, waveguide "T's" and angles, flexible waveguide, etc., had to be developed. Receiver r-f components, crystals and local oscillators, and a TR box for the new wavelength all were needed. The impossibility of "preplumbing" the 3-cm magnetrons at this period led to the development of a so-called anti-TR, another glow-discharge device inserted in the line to keep the transmitter from absorbing any appreciable amount of the received signal.

Indicator Tubes

Preliminary Indicators. The key problem of the indicator group was the cathode-ray tube itself. The earliest indicator tubes used by the laboratory were those supplied by RCA under the first contract. Although they served a useful experimental purpose they were recognized as only a stop gap. They were large electrostatically deflected tubes with a 12-in. face and a screen that consisted of a single layer of phosphor having only slight persistence.

The British representatives had described in general terms the importance of having long-persistence tubes, though they had been unable to give anything but general information of reported British developments along this line. They explained however that the British used a duplex-layer screen composed of two phosphors, an inner layer emitting short flashes of blue and ultraviolet light when electrons impinged on the surface, and an outer layer emitting orange light with a slow decay when activated by the light from the inner screen. NDRC contracts were let to the General Electric Company [GE] and to RCA Victor early in 1941 to develop long-delay cathode-ray tubes along these lines. The two re-

search laboratories worked closely together in cooperation with the MIT-RL indicator section which served principally in the role of a coordinating and testing center for research and later for production control. Delicate techniques were developed for measuring the characteristics of the phosphors in tubes submitted by GE and RCA.

Development of Standard Tubes. By the summer of 1941 what have become essentially standard tubes were adopted by the laboratory. These were for general use, but were especially suited to airborne installations, being smaller and more compact than earlier experimental models. They were tubes with a flat face, and a duplex-layer persistence screen. Seven-inch and 5-inch tubes were designed, in which the electron beam was focused and deflected by a magnetic field, instead of by electrostatic means. Large-scale production was begun at GE and RCA.

For AI work these tubes were adapted to produce so-called Type C scan, with a rectangular image in which elevation is plotted against azimuth and a Type B scan giving range against azimuth. The improved cathode-ray tubes were also used for the *plan-position indicator* [PPI] built in the laboratory during 1941. The work was undertaken on the basis of general information about the British PPI development, but without specific design data. This type of indicator has a linear sweep that takes its origin at the center of the tube. The sweep is rotated in synchronism with a rotating paraboloid. The laboratory's first PPI, which was probably the earliest built in this country, was a magnetically focused and deflected tube with coils which were mechanically rotated. It was developed for an experimental shipboard system on the USS *Semmes*. An electrostatically deflected tube was built at nearly the same time for the earliest experimental 10-cm ASV system. By the middle of 1942 two types of PPI indicators had been devised: one with a mechanically rotated coil and one with a fixed coil using selsyns to provide the proper vector components.

Synchronizer Unit

Late in the year an important change was made in the synchronizer unit. It was incorporated into a single box with the indicator circuits to produce the unit called the control central or indicator central. This important component became a central timing device, the heart of the modern radar system. It establishes the pulse recurrence rate, starts the modulator, which in turn operates the magnetron, and produces sweep voltages for the indicator tubes that are synchronous with the transmitter pulses. Much attention was paid to developing circuits for a high-speed 1-mile sweep. At about this same time circuits were devised to introduce range markers electronically on the sweeps.

3.3 WHAT HAPPENED TO PROJECT I: AI

3.3.1 Demonstration of Experimental AI Equipment

In a conference held on January 17, 1941, at Wright Field, attended by MIT-RL physicists and British representatives, the Army spokesmen expressed their doubts as to the desirability of installing AI-10 equipment in the Douglas A-20-A attack bomber, as had been tentatively suggested, and instead, made known their preference to have the equipment designed for installation in the P-61, then in the mockup stage at the Northrup plant. It was agreed that a trial installation in an A-20-A might serve as an intermediate step. In February the Army asked MIT-RL to provide equipment for 15 experimental P-61's and for one nightfighter version of the Douglas XA-26-A attack bomber.

The B-18-A equipment, improved by general tinkering and by the incorporation of the Lawson TR box and the addition of better indicators, was demonstrated to Sir Hugh Dowding, Commander of the RAF Fighter Command. During the month of July this experimental system was flown to Wright Field and demonstrated to the U. S. Army Air Forces.

3.3.2 Development and Production of SCR-720

Early in April, soon after the initial flights of this flying laboratory, a so-called A-20 version of the AI equipment was assembled in a mockup in the roof laboratory. Late in May, this system was sent at the U. S. Army's request to BTL in the care of two MIT-RL men who were loaned to BTL for the rest of the year to help engineer a

finished set. From this cooperation emerged the first production AI set, the SCR-520, of which 50 were produced by the Western Electric Company before the end of 1942. This set, of which only about a hundred were ever produced, was modified shortly after Pearl Harbor into the first production ASV set, the SCR-517 or ASC which was produced in considerable numbers. Its much improved lineal descendant, Western Electric's SCR-720, in which BTL engineers incorporated the latest improvements in 10-cm art, actually became America's standard nightfigher radar installed in the P-61's, the much publicized Black Widows. The 720's began to come off the production lines in the spring of 1943 and several thousand had been delivered by D-Day.

A second system destined for an A-20 aircraft was completed at MIT-RL in June 1941. The plane that was being modified to receive it had not yet been delivered, so the set was taken to Wright Field where it was demonstrated for several weeks in a trailer parked on a nearby hill. The system was finally installed in the A-20 plane and flown for the first time late in September and handed over to the Army for tactical experiments at Mitchel Field. Shortly after the attack on Pearl Harbor this plane was flown to the West Coast where, it is reliably reported, it constituted America's entire nightfighter protection in the event of an invasion of the Pacific Coast.

In June of 1941 an American AI-10 system prepared for installation in a Canadian Boeing 247D was taken to England by an MIT-RL representative for comparison with the British experimental AI-10 which had reached approximately the same stage of development. The important discovery was made during these comparative tests that the American transmitter gave much more power than the British, but that the British had developed a more sensitive receiver. The performance of these two systems was therefore roughly comparable. Great improvement resulted when the best features of both systems were subsequently combined. The Americans adopted the British-type crystal mixer in place of the tube mixer and brought back the soft Sutton Tube TR box.

During this period of testing, the laboratory began procurement of the components for the fifteen P-61 sets and for ten comparable sets which the British had requested for installation in Beaufighter aircraft for the RAF. As the year drew to a close it was increasingly evident that Service interest in "crash" procurement of AI equipment was less than acute; the production of the P-61's had been seriously delayed and they could be taken care of by production radar equipment when it appeared; the British also showed signs of losing interest in AI, for the last phase of the Battle of Britain had clearly been won. The course of the war, even before Pearl Harbor precipitated us into the struggle, indicated that some of the other functions of radar, particularly ASV, were to become extremely important.

3.4 PROJECT II: FIRE CONTROL AND AUTOMATIC TRACKING—SCR-584

The development of gunlaying radar at MIT-RL was much less influenced by British requirements and British specifications than had been the case with AI. This was in part because the British Technical Mission had entrusted the problem of a microwave antiaircraft set, along lines already being followed in Britain, primarily to the National Research Council in Ottawa. At MIT-RL, therefore, the development proceeded along quite original lines.

3.4.1 Antenna Scanning

OBJECTIVE

Project II was not officially undertaken by a special group in the laboratory until January 1941. It was decided that the microwave radar should be a precision system, using the novel principle of conical scanning to produce accurate pointing, and embodying the important feature of wholly automatic tracking in azimuth and elevation. Once the system had picked up a target, for example an enemy aircraft, it was proposed to have it lock on and follow, the antenna continuing to point at the target despite high speeds or violent evasive action. Data on the plane's three coordinates would be continuously fed to a gun or searchlight director.

THEORY OF OPERATION

Conical Scanning. In conical scanning the beam from the antenna is rotated at high speed

about the axis of a paraboloid, so that it describes a cone of revolution with its apex at the antenna. This produces the same effect as simultaneous lobe switching in the horizontal and vertical planes, that is, the rotating beam overlaps itself only at the axis of the paraboloid, and produces what is tantamount to a narrow pencil beam along the axis. The strongest signal is received from a target at which this pencil beam, and hence the axis of the paraboloid, is exactly pointing. Conical scanning was first experimentally produced by wobbling the entire paraboloid, later by spinning an eccentrically placed dipole. With the proper circuits, the angular deviation of the target from the axis of the parabolic reflector can be detected and converted into an "error signal." This in turn is converted by means of commutating circuits into a d-c voltage which drives the servomechanism and keeps the antenna pointing at the target. Before the appearance of production equipment automatic tracking in range supplanted manual tracking.

Range Measurements. To profit by the accuracy in range measurement inherent in radar pulses, extremely precise range circuits were devised to produce special high-speed sweeps. A special range unit or synchronizer was built which produced sweep-generating voltages for the cathode-ray tubes, generated the trigger pulse to the driver unit of the modulator, and provided the range gates designed to eliminate target confusion, which is one of the principal obstacles to automatic tracking. For example, when two targets are at the same bearing and nearly the same slant range, the antenna may hunt between the targets or take up an intermediate position between them. Range gates are designed to remedy this difficulty by confining the reception of signals to a short interval of time, i.e., to a portion of the indicator trace. The so-called "Narrow Gate" first used in the experimental equipment, and the still narrow N^2 Gate, were important features of MIT-RL fire-control radar.

Experimental Systems

A Project II roof system went into operation in February 1941 using what AI components could be borrowed from the higher priority AI program. Using a specially modified 30-in. paraboloid, a crude demonstration of conical scanning was possible by February 6. Although the most successful equipment to result from these early experiments was the mobile SCR-584, embodying all the features described in preceding text, the first efforts were directed toward using the conical scanning feature, without the addition of automatic tracking, for an airborne radar gunsight and for a ship fire-control system.

Airborne Gunlaying Radar. The aircraft gunsight program, which was somewhat premature, never went beyond an experimental installation demonstrated at Wright Field in January 1942. The program of airborne gunlaying radar had to await the development of the lighthouse tube transmitter which permitted the design of compact lightweight systems. The U. S. Navy program resulted in what was chronologically the earliest (if not the most fruitful) production contract resulting from MIT-RL research and development. An experimental 10-cm gunlaying radar was tested at the Naval Proving Ground, Dahlgren, Virginia, during September and October 1941. After a conference at the Bureau of Ships [BuShips] in January 1942, a contract was awarded to the Western Electric Company to build the Mark 9 radar based on the model that had been demonstrated. MIT-RL severed connections with the project at this point. Only a handful were ever built and none was ever installed because the gun director for which they had been designed was cancelled. A similar fate was met by the Mark 10, a slightly improved Mark 9, though a few were installed on light cruisers. Of the Mark 19 radar, a repackaged version of the Mark 10, about a hundred units were finally produced. Although later designs were greatly improved, microwave radar fire control, despite its potentialities, never became a main reliance of the fleet.

Aircraft Scanning and Automatic Tracking. The delivery by GE late in May 1941 of an amplidyne-controlled aircraft machine-gun turret on which a paraboloid could be mounted, made possible the first demonstration of automatic tracking in elevation and azimuth. This success led the laboratory to build a mobile, truck-mounted unit, the XT-1, to serve as an experimental system for further research. The system had both conical scanning and automatic track-

ing. It was not originally intended that the XT-1 should become a model for a specific military weapon, and work was undertaken in July 1941 without specific Service request. The system was, however, demonstrated to the Signal Corps in December; and in February 1942 it was tested by the Coast Artillery Board, where it displayed its ability to locate objects within less than a mil (1 mil = 0.06°) in azimuth and elevation and within 20 yd in range. This performance together with its capabilities in automatic following, led the Antiaircraft Artillery Board to conclude that XT-1 was superior to any equipment yet tested for the purpose of furnishing present position data to an antiaircraft director. As a result of these tests it was proposed to design a microwave and antiaircraft radar to be based on the XT-1. It was to be equipped to feed data to the M-4, M-7, and M-9 Army directors which in turn would be coupled to 90-mm power-driven antiaircraft guns. It was decided also to incorporate a PPI so that the set could do its own searching, and dispense with an associated search radar to put it on the target. In April 1942 the Signal Corps placed an order with GE for 628 units of the SCR-584. Later this number was increased to nearly 2,000 and the production divided between GE and Westinghouse. This order was subsequently reduced by the Signal Corps.

The SCR-584 differs little from the prototype in fundamentals. The numerous improvements were almost entirely of an engineering nature, carried out by GE engineers in consultation with MIT-RL.

Application of SCR-584

Experimental Use. The XT-1 not only served its purpose as prototype and testing unit during the entire design stage of the production of the SCR-584, but it was employed, with a success that surprised even its designers, as an experimental instrument for the careful tracking of high-speed targets. It was used successfully to determine the performance of new airplanes in high-speed dive tests, when for physiological reasons human pilots could not fly the plane and record the results, and when airborne recording instruments were unreliable. It was found able to determine the muzzle velocity of shells and the trajectories of shells or bombs. With the addition of special recording equipment, the XT-1 proved of great value in tracking aircraft during experimental and training bombing flights. The technique involved here was later adopted in the operationally important technique of close-support bombing.

Field Application. The first production SCR-584 was delivered on July 15, 1943. Out of a total of about 1,600 sets supplied to the Army, about 1,400 had been delivered by June 1944. The set made its operational debut on the Anzio Beachhead where its accuracy in shooting down German bombers, and its relative invulnerability to the jamming which had virtually silenced the SCR-268's, contributed to the successful landing of supplies and the expansion of the beachhead. In the defense of the London area against the post-invasion onslaught of the V-1 flying bombs, the SCR-584 was used with spectacular success in conjunction with two other signally important weapons, the proximity fuze and the M-9 gun director developed by BTL. On the Continent, the SCR-584 was an important element of the defense of the Antwerp region, and was used in a new role, in conjunction with the MEW, in controlling and directing tactical air support of the ground troops. Although introduced more slowly into the Pacific Theater, it had already been in a number of important actions and was defending important supply bases at the time war ended.

Another fire-control development, the Mark 35 radar and its partner, the Mark 56 director, did not see action in World War II, but will be mentioned in Chapter 7 because it is a natural evolution of the automatic tracking developed in SCR-584.

3.5 MICROWAVE RADAR OVER WATER SG, SCR-582, ASG

The discovery in March 1941 that microwave radar performed admirably over water, led the laboratory to explore more thoroughly this behavior of microwaves and to design sets to utilize it. In the spring, the roof group expanded its activities to become a systems group for the development of types of radar not in the province of Projects I, II, or III. This group of physicists and engineers built the first microwave ship-

board equipment, the first ASV systems and the first microwave system for coast defense and harbor-entrance control duties. These systems were all characterized by being relatively straightforward adaptations of the AI-10 systems, with the incorporation of the PPI as the only significant innovation.

3.5.1 Shipborne Systems

Preliminary Tests

In April 1941, the U. S. Navy granted permission to the laboratory to install an experimental ship-search system aboard the USS *Semmes*, a "four-stacker" destroyer of World War I type, operating out of New London, Connecticut, under Lt. Comdr. (now Capt.) W. L. Pryor, Jr., and assigned to radio and underwater-sound experimental work. Installation of the microwave equipment aboard ship began on May 6, and the first signals were obtained a week later with an A-scope. The first PPI signals were obtained aboard the *Semmes* on June 5, 1941. Between June 9 and July 1 the ship made coastwise cruises which gave excellent opportunities for observing the system at sea. Land signals were picked up at 19 miles and ships were followed to a distance of about 7 miles. During the rest of the summer and the fall innumerable changes and improvements were made in this flexible experimental equipment. By November the system was giving 4 miles range on submarines, 8 miles on aircraft, and 26 miles on land.

Development of SG Systems

Navy Installations. In June 1941, the Navy placed its first microwave radar contract with the Raytheon Manufacturing Company to develop, with the assistance of MIT-RL, a shipboard microwave set based on the experience of the *Semmes* installation. In the development of this system the Raytheon Company, the Naval Research Laboratory, and Massachusetts Institute of Technology Radiation Laboratory can all claim a share. The resulting system, the rugged SG, has been the microwave set most widely used in the fleet, where it was especially valuable for station-keeping, as a navigational aid, and for low coverage general warning. The first production unit, apparently the earliest production microwave equipment, was installed on the USS *Augusta* and shipped out on April 5, 1942. Over 1,300 SG's (including their improved versions, the SG-1's and SG-a's) have been produced. They have been installed on nearly all classes of vessels of the fleet: on battleships, carriers, heavy cruisers, light cruisers, and destroyers.

Coastal and Harbor Installations. During the summer and fall of 1941 an experimental 10-cm system, closely resembling the system aboard the *Semmes*, was installed in a truck to study the possible use of this type of equipment for harbor control purposes and coast defense. On November 18, it was set up on Deer Island, a small peninsula commanding the principal channel into Boston Harbor and the site of a harbor-entrance control post jointly operated by the Army and Navy. So successful was the equipment in aiding the work of the control post, by supplying accurate range and bearing on all ships entering or leaving the harbor, that after Pearl Harbor this experimental laboratory equipment remained on 24-hour duty until replaced by production equipment. As a result of visits to the Deer Island installation by Army and Navy officers during December of 1941, the Army ordered a crash production of 50 sets based on the RL truck system. The production of these sets was undertaken by the Research Construction Company, Inc. [RCC], NDRC's factory-sized model shop, which went into operation late in 1941. The first of these production sets, to which the Signal Corps assigned the designation of SCR-582, was installed in June 1942, at the Boston harbor entrance control post. Five of the original crash units accompanied the American forces in the North African invasion, and were the earliest microwave ground equipment to see action. Late in 1942, two modified SCR-582's, provided with a larger paraboloid and, in order to get greater range, a high-powered modulator were sent to the Panama Canal Zone to supplement, by their low coverage, the longer-wave early-warning network.

3.5.2 ASV Microwave Radar

Preliminary Tests

The possibilities of microwave ASV equipment had been mentioned many times in early

discussions at MIT-RL. The first steps were taken in the spring of 1941, shortly after the historic flight in the B-18 flying laboratory, when the roof group initiated the adaptation of AI equipment to ASV purposes. An experimental set was built and installed during the summer in the first of many aircraft which the Navy assigned to the laboratory for experimental work. This was an XJO-3, a Lockheed transport which had been specially adapted to this new job by the Naval Aircraft Factory in Philadelphia by the addition of a plywood nose, and other changes. The first airborne PPI was built for this system. The system's performance was carefully tested on a number of flights out of Boston and Philadelphia. It improved so noticeably that on September 26, in an attempt to test the ability of the system to work through the overcast, a ship was picked up from 8,000 feet at a distance of 40 miles. The PPI operator guided the pilot until he could see the ship from 2,000 feet.

In September BuShips authorized MIT-RL to carry out further tests on microwave ASV with a view to helping the BTL develop an ASV-10 for the U. S. Navy. It was finally decided that a semioperational installation should be made in a Navy PRM-1, a twin-engine Martin flying-boat. A system was assembled during December and first flown on January 3, 1942, on a trip from Boston to Philadelphia. The installation was carefully tested on flights out of Norfolk and from bases in Florida during January and February. At Banana River, Florida, comparative tests were run against a British ASV. By May 1942, the system had been operated a total of 156 flying hours and was reported as capable of detecting cargo vessels at 45 miles and submarine conning towers at more than 15 miles.

Although it had originally been intended that the XJO-3 and PBM-1 systems experience should find expression in the ASC, the ASV system which BTL were designing for the Navy, the influence was actually felt more directly in a set designed during 1941-42 at the MIT-RL for the British and, independent of the BTL, for the U. S. Navy.

Field Trials

At the end of July 1941, a representative of the British Air Commission arrived at MIT-RL to explore the possibility of acquiring a small number of microwave ASV sets for use by the Coastal Command. These were to be installed in Liberator bombers being supplied to Britain under lend-lease. Two specially modified Liberators, known as Dumbo I and Dumbo II, doubtless because the bulbous radar dome beneath the nose enhanced the planes' already elephantine appearance, were equipped with prototype units of microwave ASV during the winter of 1941-42. The Dumbo I equipment flew for the first time from the East Boston Airport on December 11, 1941, the day Germany and Italy declared war on the United States. It was successfully demonstrated shortly thereafter to British and American officers and was flown to the United Kingdom in March 1942, where it underwent trials in Northern Ireland during April. The second Liberator was rapidly equipped and demonstrated at the end of April to the Secretary of War, General Marshall, General Arnold, and other high ranking officers. These two systems served as prototypes for a crash program of 17 similar systems manufactured by the Research Construction Corporation, of which 14 were for the British. The first of these DMS-1000 sets was handed over to the British representative in August 1942; the remainder had been delivered by December 1942.

By the time the British received their first production unit, MIT-RL's ASV equipment had already seen Service use and drawn blood from the enemy. The story of the 10 B-18 ASV equipments hastily thrown together at U. S. Army request early in 1942 is of great importance in the history of the laboratory. Their success gave the organization much-needed confidence and a sense of direct participation in the war and in large measure made up for the disappointing and inconclusive end of the AI program.

Bomber Experience

At the conference between MIT-RL personnel and representatives of the Air Forces held at Wright Field shortly after the Pearl Harbor attack, one of the officers present urged that it would be extremely valuable if a number of B-18 aircraft or some similar type could be equipped on a crash basis with ASV equipment for Pacific patrol work. It was agreed that for lack of air-

craft the laboratory AI program had slowed up beyond resuscitation and that the components intended for the British Beaufighters could be used, with only slight changes, for this purpose.

The RL-AI specialists were put on this new problem, while the Army Air Forces brought together from various parts of the country, under the command of the late Col. William C. Dolan, ten somewhat shop-worn B-18 planes. The planes and their crews began to arrive at the East Boston Airport in February 1942. Working at high speed, MIT-RL installed equipment during the winter in all ten planes, provided the necessary spares, and equipped a testing and repair truck to service the sets.

As the installations neared completion, it was decided not to disperse the planes, but to assign all the crews, at least temporarily, to Langley Field, where the first planes had already returned, late in March, with their new microwave equipment. Even before all the planes had left Boston, the first operational successes were recorded. On April 2, one of the ASV-equipped B-18's, piloted by Colonel Dolan, and with two MIT-RL staff members in charge of the equipment, shared in the rescue of a Navy observation plane that had been forced down fifty miles at sea near Boston. The floating plane was located by means of the B-18's microwave radar equipment and a destroyer was guided to the rescue.

From Langley Field the first B-18's were already acquiring operational experience against German submarines swarming off the East Coast. On April 1, 1942, a B-18 on its first night patrol, homed unsuccessfully on an enemy submarine, somewhat later picked up radar signals from a second submarine, which disappeared before a run could be made, and finally picked up a third submarine at a range of 11 miles from an altitude of 300 feet, homed on it and sank it. Another kill was made on a flight from Langley Field on May 1. On May 22 five of the crews were ordered to Key West and five to Miami, where they operated until June 19, making one attack, the results of which were undetermined.

In July 1942, the first sea-search-attack group [SSAG] was activated under Colonel Dolan's command. This unit, consisting at first only of the B-18 crews, was intended to serve as a development and training unit to try out new antisubmarine weapons and evolve a tactical doctrine. Seven of the B-18's with their MIT-RL equipment (three planes had suffered operational damage beyond possibility of repair) remained with the group until its inactivation in July 1943.

Following the aggressive principle of the commanding officer that the enemy submarines should be sought out where they were known to be operating, the group was sent on detached service on two important occasions. Between August 15 and August 23, these planes flew 24 missions off Key West, and made 2 attacks, both believed successful. In the autumn they flew 36 antisubmarine missions from Edinburgh Field, Trinidad, which resulted in 6 sighting and 3 attacks, one of them a probable kill.

At the time of its inactivation in July 1943, the First SSAG had completed a total of 1,189 satisfactory ASV missions (i.e., without radar failure); of these 323 were made with MIT-RL equipment, the rest being with the SCR-517's and SCR-717's that this group was the earliest to test operationally. The laboratory hand-built equipment gave a higher percentage of satisfactory missions than the SCR-517's, the earliest microwave production equipment of this type.

None of the experimental ASV systems described up to this point had more than an indirect effect upon the design of production microwave equipment. The story of the ASG, however, is that of a set designed by MIT-RL, engineered in cooperation with the Philco Corporation of Philadelphia, and produced at great speed and in large enough quantities to have exerted a notable effect on the war against the submarine.

Development of Blimp Equipment

A group at the United States Naval Air Station at Lakehurst, New Jersey, expressed an interest, during October 1941, in a radar system for installation in nonrigid airships. Consultations with MIT-RL members resulted in the decision to make an experimental installation in a K-3 blimp, using MIT-RL experimental equipment recently removed from the XJO-3 airplane.

When experience had shown this idea to be sound, a conference was held at Cambridge on February 17, 1942, with Lt. Comdr. L. V. Berk-

ner and Lt. Comdr. D. T. Ferrier representing the Navy, to decide on the proper features for a production set to be installed in blimps. The ASC was considered but dismissed as too heavy and too bulky, and because production figures were not promising. It was pointed out that the Stromberg-Carlson Company was building a new, lightweight pulse modulator, based on the latest MIT-RL developments and that it was designed to meet Navy specifications for such components. A decision was reached to design a new 10-cm set around this pulse modulator and to give the production contract to the Philco Company which had already attracted the attention of the Navy by its speedy performance on earlier contracts. The set was to have a PPI, whereas the B-18 systems and the Western Electric sets, ASC and SCR-517, had B-scopes.

Final engineering design was worked out in close cooperation with the Philco engineers during 1942. Philco turned out a preproduction set in July 1942. In this same month the Navy embarked on a heavier-than-air ASG program. Philco's first production set appeared in late October 1942. By mid-December, 28 production sets had been installed in PBM-3C flying boats at the Naval Air Station at Norfolk, Va. By March 1944 Philco had delivered 4,141 sets. These were widely used by the Navy in blimps and patrol planes, by the British, and in smaller quantities by the Army.

3.6 PROJECT III: LONG-RANGE NAVIGATION (LORAN)

3.6.1 Theory of Loran

The need for a system of long-range navigation for ships and aircraft had been among the original proposals made by the Armed Services to NDRC and was discussed, as previously mentioned, during the earliest conversations with the British mission. Early in October 1940, A. L. Loomis formally proposed to the Microwave Committee that they adopt a scheme in which pulsed radio waves from fixed stations are used to produce a grid or network of hyperbolic lines from which a fix can be obtained by an aircraft or ship carrying a specially designed pulse receiver. In a simplified case, if each of a pair of synchronized transmitting stations several hundred miles apart sends out simultaneous pulses, a receiver at any point on the perpendicular bisector of the line between the stations will receive the pulses simultaneously. At all other points within range of the stations there will be a fixed difference or delay in the time of arrival of the pulses, the value of this time difference depending only upon the geographical position of the receiver. The locus of those points on the earth's surface having a constant time delay is one of a series of confocal hyperbolic lines generated by the pair of stations. The time difference determined by a special pulse receiver-indicator can then yield a line of position. When the time delay from a second pair of stations is translated into a second line of position, the result is an accurate navigational fix.

3.6.2 Development of Loran

Loomis' proposal was adopted by the Microwave Committee, and a coordination committee for Project III was set up to arrange for the procurement, field installation, and testing of suitable equipment. A frequency of about 30 mc per sec was chosen. A transmitter with peak power of 2,000 kw was specified; but the exact pulse rates and methods of synchronization were not settled when the original equipment was ordered in December 1940.

After the organization at MIT-RL the technical responsibility was assigned to a special navigation group set up in January 1941 under the direction of Melville Eastham. During the spring of 1941, while awaiting the delivery of the Project III equipment, this group concentrated upon a technical reconsideration of all aspects of the proposed high-frequency system. This review resulted in the small-scale development during the summer of 1941 of a system using medium frequencies. The initial tests were so successful that the original high-frequency plan was abandoned early in 1942. This new system became known as *long-range navigation* [LRN] and these letters were later expanded into the word *Loran*.

The basic evolution of the Loran system was virtually completed by September 1941 when the present system of receiving and comparing the time of arrival of pulses was evolved. This highly precise time-measuring technique used precision

circuits similar to those of the radar range unit and a cathode-ray tube indicator with a double trace. The pulses of two stations appear on the separate traces, which are carefully marked off by electronic time markers. By superimposing the pulses the time-difference can be read directly from the scale with an accuracy of about 5 msec.

Tests of Experimental Models

Low-power field tests were run in December 1941 and January 1942 from two shore stations located at Montauk Point, L. I., and Fenwick Island, Delaware. Observations were made from Bermuda. The unquestionable success of these trials led to the expedited production of new high-power (100 kw peak power) transmitters for a demonstration in June 1942, when a Navy blimp carried aloft an experimental airborne receiver-indicator for the first full-scale test of this system of navigation. Shortly after, observations were made over an extended period from a Coast Guard weather ship in mid-Atlantic.

3.6.3 Field Applications

Station Network Installations

The success of these demonstrations aroused intense Army and Navy interest. Early in 1942 arrangements were made for the Navy to underwrite the production and early installation of a number of shore stations and shipboard receiver-indicators by the MIT-RL. The first 14 transmitter-timers were manufactured before the end of 1942 by MIT-RL and RCC. The first 8 transmitters were produced in the same period, 6 by the Harvey Radio Laboratories, and 2 by Canada's Research Enterprises, Ltd. The Fada Radio and Electric Company of Long Island City, N. Y., produced the first 50-or-so shipboard receiver-indicators.

In anticipation of formal Service backing, arrangements had already been made with the Royal Canadian Navy for the erection of two stations on the coast of Nova Scotia under the direction of MIT-RL personnel. During the summer of 1942 three more stations were sited in Newfoundland, Laborador, and Greenland, and every effort was made to get the entire seven-station system in regular operation before the winter. The four southernmost stations, linked together so as to provide three pairs, began regular service on October 1, 1942. Unforeseen difficulties kept the remaining stations from regular operation until the following spring. By July 1943 the chain was officially turned over to the U. S. Coast Guard and the Royal Canadian Navy. Subsequent installations during 1943 in the Aleutians and the northeastern Atlantic were handled entirely by the Coast Guard and the British Admiralty, respectively. The equipment for these so-called standard Loran installations was wholly, or in large part, of MIT-RL design. Moreover, the critically important timer units for these installations were manufactured solely by RCC and MIT-RL. During the second half of 1944, and in 1945, a very large area of the Pacific Ocean was covered by Coast Guard Loran installations made under Navy auspices at the direction of the Joint Chiefs of Staff.

The group that accomplished these results was never very large. In July 1941, it was composed of 10 staff members and two technicians. Two years later it had reached its maximum size of 73 persons, including 39 staff members. From the first, the essential differences between the work of the navigation group and the radar work of the rest of MIT-RL was recognized by the Microwave Committee, which set up a subsection to coordinate the Loran activities. This later became Section 14.2 of NDRC and finally was dissolved when the Services took over general supervision of the project. While in existence, this subcommittee arranged for the complete segregation of Loran research and development, as well as purchasing, shipping and field station operation, from the rest of the laboratory. At the Navy's request, special security measures were adopted.

Special Installations and Applications

Skywave Synchronization. During the spring of 1943, the navigation group worked out the idea of synchronizing a pair of Loran stations, not by the directly transmitted ground wave, but by means of the sky wave reflected at night from the E-layer of the ionosphere. This technique made possible the nighttime use of baseline distances of 1,200 to 1,400 nautical miles, which meant greatly improved geometrical accuracy and the possibility of navigation over land as

well as over the sea. In the summer of 1943, a system using this technique was proposed to the RAF and accepted by them pending a successful test in this country, for use in nighttime operations deep in enemy territory. This full-scale field test was successfully completed late in 1943. In the early fall of 1944 the system was placed in full operation, giving reliable nighttime fixes over all of Central Europe and as far east as Warsaw. After several months of trial use on a relatively small scale, it was discovered that the system had a sufficiently small probable error to permit blind bombing with an accuracy that compared favorably with radar techniques. A total of about 22,000 bombing sorties were flown by the RAF using SS (skywave synchronization) Loran.

Navigational Aid in Pacific Theater. Toward the end of 1943, it was suggested that Loran might be used in the CBI Theater to provide a navigational aid for plane traffic over "The Hump." Simplified lightweight timers and transmitters were hastily designed and built by MIT-RL, and tested in the mountains of southern California. A chain of three stations was put in operation, under the direction of one of the most experienced MIT-RL Loran engineers, in the Assam region of India late in 1944. A second triplet went into regular operation in the Kunming area early in 1945.

Low-Frequency Loran. At the close of the war MIT-RL was engaged in an important development described as low-frequency Loran. Early experiments had made it clear that longer ranges could be achieved by using lower radio frequencies than the 2-mc per sec band which had been assigned to wartime Loran for reasons of expediency.

The first experiments were performed in the winter and spring of 1944 and by April 1945, with joint Army-Navy backing, a full-scale three-station low-frequency system was in operation on the east coast of the United States using a radio frequency of 180 kc per sec. Equipment for eight permanent installations of this sort was in the process of crash procurement for the Army Air Forces at the time of the Japanese capitulation. The field tests indicated that low-frequency Loran can provide reliable twenty-four-hour service with ranges of about 1,500 nautical miles in most areas of the world. The peacetime possibility of improved Loran in an age of global air transportation can scarcely be exaggerated.

3.7 RADAR ON THREE CENTIMETERS

3.7.1 Early Experimental Objectives

From the very earliest days of the laboratory's program, it was generally understood that a strong effort should be made to devise microwave radar on a wavelength even shorter than 10 cm. To conservatives in military procurement this must have seemed a doubtful enterprise. It was already presumptuous enough to try to develop 10-cm equipment to supplant the longer-wave radar which was only just going into production. To expect equipment on still another unexplored wavelength to be ready in time to be of use was no less than audacious. The problem at MIT-RL was what wavelength to choose, for it was possible either to attempt a radical improvement by going to a wavelength as short as a few millimeters in length, or to stay closer to 10 cm in a region where techniques already being perfected could be readily adapted, by scaling-down and other modifications, to the new wavelength. The choice of 3 cm was a somewhat arbitrary compromise. It was close enough to 10 cm to offer a fair chance of success in a reasonable length of time, yet the gain of more than threefold in resolution would be worth a very considerable engineering effort.

3.7.2 Experimental and Preproduction Systems

Deer Island Trials

The emergence of the first successful 3-cm magnetrons from the Raytheon model shop in the early spring of 1941 made possible the creation of an advanced development group at MIT-RL whose task was to build an experimental roof system. Such a system was in operation in the middle of May 1941, giving echoes from ground objects six miles away with a 12-ft paraboloid. It was followed soon after by a similar system installed in a truck. This was placed in operation at Deer Island in Boston Harbor shortly after the attack on Pearl Harbor, and operated side by side with the XT-3 (10-cm)

truck system for almost three months, demonstrating its superiority over the 10-cm system in obtaining much higher resolution of targets.

AIA Fighter Plane System

On May 21, 1941 a discussion took place between E. G. Bowen of the British mission and L. A. DuBridge, the director of the laboratory, during which it was agreed that the success of the 3-cm development suggested an immediate application in an AI for single-seated fighters. Proposals were drawn up for this development. The AIA program only took definite form when, in September 1941, the Navy expressed its interest in a combined interception and gun-aiming radar for its carrier-based nightfighter version of the Vought-Sikorsky F4U-1 aircraft. The specifications called for a compact radar having a weight of not more than 250 pounds, an antenna system with negligible drag, an accuracy sufficient for blind gun-aiming, a useful search range of two miles at altitudes of 2,000 or more feet, and a minimum dependable range of 500 feet. The laboratory representatives were convinced that a 3-cm AI with a specially designed scanner and indicator could be built to satisfy these requirements. At almost the same time the Navy was persuaded to sponsor a simultaneous development by a newly created high power group of the MIT-RL of a height-finding and general control set for aircraft carriers. This set, which became the SM, will be discussed below.

Initially the MIT-RL was asked to build three systems, one experimental and two preproduction versions of the AIA, while advising the Sperry Gyroscope Company in the design and construction of ten preproduction systems. The laboratory's experimental system was completed and tested early in June 1942 and was delivered to Quonset, R. I., for pilot training late in the same month. The two preproduction systems were completed by late October. With the assistance of the laboratory, Sperry's first preproduction set was finished and tested in April 1943. By June 1943, the company had delivered its ten preproduction sets. In October 1944 Sperry completed its production of 604 sets.

AIA-1 Improved System (AN/APS-6)

In April 1943, having virtually fulfilled its commitments on AIA, the laboratory turned its attention to the development of an improved 3-cm AIA called the AIA-1. This set was to operate at an altitude of 30,000 or more feet and was to incorporate such important new developments as a 3-cm magnetron with higher power perfected in the interim. But the prime impetus for the AIA-1 program came from the installation difficulties encountered with the AIA. In both sets the scanner was placed in a wing nacelle, and in the earlier set this meant running lengths of waveguide through the airplane wings to carry the r-f energy from the magnetron to the paraboloid. The AIA-1 was made possible by the development at MIT-RL of an important device called a pulse transformer which amplifies pulses of energy without appreciable distortion. This, in turn, made it possible to eliminate the long waveguide by placing the magnetron immediately back of the paraboloid in a unit called the r-f head which also included the pulse transformer, the TR box, and other r-f components. This improvement had first been introduced in the parallel 3-cm ASV development, to be discussed shortly.

The MIT-RL completed its own experimental system in September 1943 while assisting Westinghouse in the design and development of a production set. Westinghouse sent its first preproduction set to the laboratory for tests on December 1, 1943. Five months later the company delivered its first production unit of AIA-1 to which was given the joint Army-Navy designation of AN/APS-6. A total of 791 sets had been delivered to the Navy by Westinghouse by April 1945. The AIA-1 proved to be a much sturdier and better designed set than its predecessor and was being used in increasing numbers in conjunction with the SM aboard carriers of the fleet as the war came to an end.

ASV Radar Equipment

Preliminary Investigation. In the autumn of 1941, coincident with the inception of AIA, preliminary investigations of 3-cm ASV applications were being made by MIT-RL at the request of the Navy. As early as November 1941 components were being assembled at the laboratory for installation in a Navy JRB aircraft, a two-motored general utility transport, assigned to the use of the laboratory at the East Boston Airport. This set, wholly experimental and not de-

signed as a prototype of any development, was completed and flight tested in June 1942. Much flying was done during 1942 and 1943 to explore the behavior of the new frequency. The PPI photographs made from the air with this first higher-resolution microwave radar showed at once the great superiority of the new equipment. The greater detail and fidelity with which the 3-cm image reproduced the natural features below the plane caused great excitement among those in the laboratory and in the Armed Services who were following this development.

Torpedo Bomber (ASD) Radar Development. Meanwhile the Navy had been discussing with the laboratory the advisability of developing a 3-cm production ASV equipment. In a report dated February 6, 1942, the laboratory formally submitted its proposal for a 3-cm equipment, the ASD, for installation in the Grumman TBF. The radar would be designed to furnish the pilots of torpedo-bombers with information as to the position of surface vessels, especially at night or during overcast conditions.

The Navy contracted with the Sperry Gyroscope Company to develop a prototype (XASD) and to manufacture production sets based on that prototype. The laboratory accepted the somewhat vaguely defined position of adviser to Sperry during this development.

Initially the XASD set used a 10-kw magnetron, the output of which, as in the AIA, had to be fed through a long length of waveguide to an antenna assembly in a nacelle on the wing of the airplane. After considerable difficulty and many delays, largely inherent in the difficulty of this design, the XASD was installed and successfully test-flown in a Grumman TBF at the end of June 1942. With help from the laboratory, Sperry completed its experimental preproduction set in July 1942. Ground tests were finished in August and Sperry began production immediately. Although the ground and flight tests of the XASD and of the preproduction set had been successful, the first production sets were not satisfactory. Dissatisfaction with them had two results; first, research was started in the fall of 1942 on a new and improved set to be known as the ASD-1; and, second, the production model of ASD was considerably modified and improved. Originally planned for the TBF plane, the ASD sets were diverted for installation by the Navy in PV-1 aircraft (Vega Ventura patrol bombers). By June 1943, 600 ASD production sets had been delivered to the Navy; by April 1944 the complete order of 3,400 sets had been completed.

Patrol Bomber (ASD-1) Radar Development. In a conference at MIT-RL on November 25, 1942, the Navy and the laboratory initiated the ASD-1 program with the Philco Corporation as manufacturer. The essential differences between ASD and ASD-1 were to be an improved antenna, a more stable and accurate indicator, a 40-kw magnetron, and the addition of a specially designed r-f head, based on the recently developed pulse transformer. As in the AIA-1, this eliminated the long waveguide through the wing to the antenna in the wing nacelle. Although designed for the Grumman TBF and the Vought-Sikorsky TBU it was specified that the ASD-1 should be adaptable to the PV-1 airplane.

3.7.3 Development and Production of AN/APS-3

MIT-RL was made a consultant to the Navy in the Philco contract, instead of an adviser, a decision which reflected an important change in the laboratory's relations with the manufacturers. The responsibilities of the laboratory during the development and production stages of a project had up to this time not been clearly defined. In certain instances progress had been severely impeded because differences of engineering opinion arose between MIT-RL personnel and the manufacturer which could not be resolved by any final arbiter. This fact became increasingly critical as it became more and more evident that the laboratory could not abandon a project at the experimental or breadboard stage as had been the tendency at first, but must follow it through development and production and even into field use. Experience had shown that a sterilizing deadlock was more liable to ensue when the laboratory cooperated with the larger concerns having imaginative and forceful research groups. Their long-established engineering departments with traditional ways of doing things did not always take kindly to proposals from a newcomer. It was at about this time that the laboratory evolved a policy of working to a

large extent with smaller electronic concerns, or at least with companies having modest research and development organizations. MIT-RL became the design and development organization for a group of companies the production facilities of which were thereby brought in to relieve the already crowded schedules of the four large electrical concerns which the Army and Navy had been in the habit of entrusting with its contracts. Late in 1942, the notion of consultant status was evolved in conversations between the U. S. Navy and the MIT-RL to provide a formula by which the laboratory could continue active participation in the development of equipment as it went into production.

In January 1943 Philco sent three engineers to the laboratory to work on a prototype. This was another new departure and an effective one. Where the laboratory had previously sent its engineers to advise a manufacturer at his plant, Philco reversed the procedure. With the approval of the Philco management, which agreed that two research organizations would only impede one another's activity, MIT-RL served as the development group working directly with Philco production engineers, almost as part of the Philco organization. Philco's own small but able research group was thereby freed to work on other problems. The Philco engineers completed their prototype at MIT-RL and shipped it to their factory. Concurrently the laboratory built an experimental XASD-1 set which underwent ground tests at the East Boston Airport during March, and flight tests during June 1943. In July, the first set built at the Philco factory was installed in a PBN patrol bomber by the Navy and tested at Anacostia. Its performance was comparable with that of the laboratory set. By the end of August, Philco had delivered nine sets, called the AN/APS-3, to the Navy. Sixteen months later that company's remarkable production line had produced a total of 4,924 AN/APS-3 sets.

Chapter 4

THE COLUMBIA RADIATION LABORATORY

4.1 FOUNDATION OF THE TUBE AND CIRCUIT LABORATORY

By the spring of 1942 the Massachusetts Institute of Technology Radiation Laboratory [MIT-RL] found itself heavily involved in an expanding 10-cm radar program and at the same time deeply committed to 3-cm airborne development based on the 3-cm magnetron developed there under the direction of I. I. Rabi. Rabi had divided his original group, soon after the attainment of this early objective, into two parts: a magnetron group under G. B. Collins entrusted with carrying on an important program of testing and improving the 3-cm and 10-cm magnetrons; and an advanced development group whose job it was to develop 3-cm components for operating systems and successful airborne equipment.

4.1.1 One-Centimeter Magnetron Project

Available Data

It was at this time that it seemed propitious to consider opening up still another band and to undertake the development of a magnetron to operate in the neighborhood of 1 cm. Experimental magnetrons at this wavelength had been made before. The magnetron group at MIT-RL had operated a tube of this wavelength in September 1941, using a 1-cm anode made for them in the Raytheon tube shop. This tube was operated on the vacuum pump. Somewhat later one or more sealed-off tubes were built by F. Hutchinson of that group, but they performed very poorly. The British, too, had been working on this problem for some time with somewhat more continuity of effort. B. V. Rollin of Oxford's Clarendon Laboratory reported in October 1941 on the successful design of a tube operating near 1 cm which gave 50 to 100 w of peak-power output.

Organization Problems

The fact that the magnetron group at MIT was already overburdened, as well as a number of related reasons, appeared to dictate the recruiting of a new team to handle the problem. This meant placing it outside the bustle of the swiftly expanding laboratory where the emphasis was increasingly on systems development.

Rabi suggested Columbia University. This suggestion, while a natural one for a member of its faculty to consider, had several special advantages. Columbia was sufficiently remote from the MIT-RL while permitting ready access to it whenever necessary; its situation permitted easy and immediate contact with BTL and with other important industrial concerns; and, as Rabi was doubtless aware, space could readily be made available. Perhaps centrally important was the fact that a New York location made it possible to bring into the radar program several highly esteemed workers with whom Rabi had been earlier intimately associated and whose personal situation made it difficult for them to leave the city.

Rabi put his suggestion before his New York colleagues late in February at an informal meeting attended by J. M. B. Kellogg, a younger colleague of Rabi's in the Columbia Physics Department; Polycarp Kusch, who until a year before had also been a member of the Columbia Physics faculty, but was then working for Westinghouse; and S. Millman, instructor in physics at Queens College.

Approval of Extended Facilities

On February 20 the suggestion for the operation of a laboratory at Columbia University was brought before the Microwave Committee which was meeting in Washington. The committee recommended that the NDRC consider the proposal for a tube and circuits laboratory and a contract with Columbia University for $140,000. It was specified that this laboratory would confine itself to developing components, and that MIT-RL would take over the development of all systems based on Columbia University components. Acting on the recommendation of the Microwave Committee, the NDRC passed on the proposal at its meeting of March 6, and in turn recommended that OSRD proceed with a contract. When this,

in turn, was approved by the Director of OSRD, Irvin Stewart wrote to Columbia giving the university an informal authorization to proceed.

Meanwhile preparatory steps were already being taken. Rabi undertook to obtain the necessary releases for Kellogg, Kusch, and Millman from their various institutions. On March 5 he visited Columbia University and conferred with Kellogg and Pegram. Dean Pegram completed Kellogg's release and after some negotiation Kusch was given a leave of absence from Westinghouse.

4.1.2 Organization of Columbia Radiation Laboratory

We may date the beginning of the Columbia Radiation Laboratory [CUDWR-RL] from Kusch's arrival on March 9 to join Kellogg. Together they made preparations to occupy half of the twelfth floor of the Pupin Physics Laboratory, space that had housed the elementary physics laboratories and which was being made ready for their use. Rabi authorized Kellogg to act in his name in all matters pertaining to purchasing equipment, hiring non-staff employees and making general arrangements. The first and biggest job was to purchase, or otherwise acquire, the necessary equipment for the laboratories and the machine shop. Equipment was borrowed or purchased from the stock room of the Columbia University Department of Physics; other items were borrowed from MIT-RL, bought in the open market, or bought upon release by the MIT-RL's own suppliers. On March 30 Kusch was able to announce that their safe had arrived and, since they were now in position to handle classified material, he hoped that certain fundamental papers that he listed would be sent to them. Since no self-respecting war research laboratory could exist without a safe, perhaps this is a preferable event from which to date the laboratory's beginnings.

Kusch and Kellogg made brief visits of a few days each to MIT-RL in Cambridge (Kusch late in February and Kellogg early in March). Millman joined CUDWR-RL on March 26 and began a month's stay at MIT-RL on that date.

By the end of June CUDWR-RL consisted of the three staff members already mentioned (Kellogg, Kusch, and Millman) and of Arnold Nordsieck of Columbia University, who had also joined the laboratory. During the course of the summer CUDWR-RL grew with the addition of two more staff members: Simon Sonkin of City College and A. V. Hollenberg.

A contract was entered into between OSRD and RCA for a tube shop for the Columbia Radiation Laboratory to be set up in that company's Harrison, N. J., plant. Kusch wrote to Rabi on June 2: "The present plan is for us to make certain tubes for lab tests on the premises and to make parts for tubes which may be completed at RCA." The shop was located in a special room of the Harrison plant and employed five people.

To carry out its part of the project (or as it turned out, to do a great deal more than that, for CUWDR-RL soon turned into a small magnetron factory) it was of course necessary to set up a well-equipped machine shop. Some of the initial difficulties in procurement were overcome when it was possible to borrow a 12-in. lathe and a precision bench milling machine from Hunter College, and a precision bench lathe and a sensitive drilling machine from City College. By the fall of 1942 the group had a fairly flourishing machine shop, and in addition a glass-blowing room, and facilities for gold and silver soldering in hydrogen, and for the manufacture of cathodes. The laboratory was already occupying all of the floor allotted to it. Besides its staff members, it now numbered four machinists, four technicians, four guards, two secretaries, two draftsmen, and a glass blower. The group remained small, in accordance with the original philosophy that attended its birth, despite a steady expansion which made the single floor the laboratory occupied singularly inadequate as far as space requirements were concerned. By April 1944, 74 people were employed at CUDWR-RL and of these only 25 were full-fledged staff members. I. I. Rabi, as a nonresident director, concerned himself less with detail than with matters of policy. He gave his subordinates unswerving support and his advice in a number of critical junctures determined the direction of the laboratory's activities. With the single exception of the associate director, Kellogg, the men at Columbia kept close to the actual laboratory benches, themselves conducting the work or directing it at close range.

4.2 TECHNICAL DEVELOPMENTS: MAGNETRONS ON 1 CENTIMETER

4.2.1 Basic Research

The work at Columbia went forward in close cooperation with MIT-RL, but with little or no attention paid to the parallel development taking place in England. There was, by contrast, close contact with BTL in all phases of the work and some exchanges with the General Electric Company [GE].

At BTL, J. B. Fisk had made some strapped 1-cm magnetrons that gave about 4-kw output. But attention at BTL shifted, in the summer and fall of 1942, to the development of the 725 3-cm magnetron. Nordsieck, of the CUDWR-RL, was borrowed by BTL to help in this work. Later Bell re-entered the 1-cm magnetron program with great vigor.

4.2.2 Development of Design and Specifications

Initial Experiments

By the end of June 1942 the first four experimental 1-cm magnetrons were built and undergoing tests. They were unstrapped tubes (since at that time strapping these tubes seemed to offer insuperable obstacles) of the vane and sector type, made by soldering the vanes into a copper anode ring. These tubes gave radiation between 0.97 and 1.0 cm, had an extremely short life of about six hours, and an almost negligible power output. Improvements were made during the summer and a meeting was held with representatives of MIT-RL, the Sperry Gyroscope Company, and BTL to decide on a value of wavelength in this range to be taken as a preliminary standard. The wavelength of 1.25 cm was chosen. The British later assented to this choice.

M 4 Tubes

By the fall of 1942 the Columbia group had turned out with their own facilities, and with some help from RCA's tube shop at Harrison, a number of so-called M 4 tubes. These were 14-slot vane and sector tubes that gave a wavelength of 1.25 cm, had an efficiency of 10 to 12 per cent, and a peak-power output of about 7 kw. These tubes seemed to have a lifetime at least of the order of 20 hours. Most of the early samples were operated on the pump (several stations were available for this work), though some sealed-off tubes were made. A number of the latter were sent to MIT-RL for testing. A series of experiments was undertaken to determine the proper size of cathode to use in these tubes.

C-Tube and B-Tube Development

In mid-autumn a tube of this sort, but with a specially designed cathode, was constructed and designated as the C tube. This showed enough promise to warrant building, during the winter of 1942-43, 50 of these tubes for careful testing. The C tube had a large cathode, the same size of that used in the 725, and the tube was operated with the same magnetic field strength as the 725.

Modification of C Tube. In the spring of 1943 the C-tube cathode was further modified as a result of the rumor that Raytheon had found in the case of 3-cm tubes that putting shoulders on the cathode, of such a sort that they protrude into the anode cavity, produced tubes of extremely high efficiencies. At Columbia the name B tube was given to tubes modified to test this assumption. The addition of this added capacity in the tube did, in fact, produce tubes of higher efficiency than anything the Columbia group had attained up to that time: in the neighborhood of 30 to 40 per cent. On the basis of what they now recognize to have been insufficient evidence they decided that these were the tubes to manufacture. But it soon appeared that the tubes were extremely short-lived and, as if this were not enough to disqualify them, suffered the additional defect of moding badly. The B tube gave less than 50 hours' service as compared to about 300-400 for the C tube.

Improvement of C Tube. Sylvania and Westinghouse had both been brought into the program as potential manufacturers of 1-cm tubes. Westinghouse soon showed itself somewhat less aggressive and successful and Sylvania emerged as the principal producer of 1-cm tubes. Sylvania delivered its first C tube on April 18, 1943, and its second almost a month later. Sharing the excitement over the apparent superiority of the B tube, Sylvania undertook simultaneous work on both tubes. MIT-RL received its first B tube from Sylvania on August 23, 1943.

E-5-TUBE DEVELOPMENTS (3J30)

The B and C tubes both had an output consisting of a pickup loop leading into a coaxial line. A waveguide output offered many advantages, especially that of making it easier to arrive at precise manufacturing specifications for the output, and making it more easily reproducible. Work was begun in the fall of 1942 on this problem, but a successful solution was not apparent until the spring of 1943 when workers at Columbia were able to report that a waveguide output tube had been built which gave 19 kw peaks at 20 per cent efficiency and 16 kw at 24 per cent. By the following autumn this E-5 tube was adopted as standard.

Sylvania and Westinghouse were advised to drop their preparatory work on the C tubes and to concentrate on the E-5's. MIT-RL received its first Columbia E-5 in November 1943 and its first 3J30 (the production designation of the E-5) from Sylvania on December 17. While production was beginning at Sylvania some 40 E-5 tubes were built and tested by the CUDWR-RL under the direction of S. Millman and A. V. Hollenberg.

MODIFICATION OF DESIGNS AND METHODS

Several important advances were made during the course of the E-5 development at Columbia and a number of different modifications in design were tried out. One of these is the Package 1-cm magnetron designed by Sonkin for use with lightweight permanent magnets. This has built-in iron pole faces and an axially supported cathode. From the standpoint of magnetron construction, perhaps the greatest innovation was the process of "hobbing" the anode crowns. In the hobbing process the anode crown is stamped out in one motion by a sharp steel cutting instrument of complex shape. The hobbing process has been in use for a number of months and it is generally attributed by the Columbia group to GE.

SHOP AND TESTING FACILITIES

CUDWR-RL was virtually its own model shop. It gave the casual visitor the impression of being composed mainly of machine shops. All the final assembly of magnetrons was done there, though many of the parts were made for them at the RCA Harrison plant. This rather reversed the original plan. A new model shop at RCA, Lancaster, Pennsylvania, helped in the later stages. It was created by special NDRC contract, originally to do work for the magnetron group at MIT, and began work early in 1944.

Much of the space at CUDWR-RL was devoted to testing magnetrons. A battery of Raytheon service modulators and of high power link modulators, both fundamentally of MIT-RL design, were clearly in evidence. The group at Columbia designed some of its own test equipment (such as a variable attenuator, a broad-band water load, and a new standing wave detector) and received useful suggestions from MIT-RL (as, for example, in the matter of the high-Q wavemeter that grew out of a suggestion of Zacharias) or used 1-cm test equipment developed by MIT, such as 1-cm spectrum analyzers of which two were sent from Cambridge. In a number of cases Rieke at MIT and Nordsieck of Columbia made developments in parallel.

4.2.3 Improved 1-cm Magnetrons

EXPERIMENTAL STRAPPED-TUBE DESIGN

At first blush it seemed improbable that the strapping technique used at longer wavelengths would be feasible at 1 cm. Sonkin and his coworkers, in May or June 1943, began the earliest Columbia attempts at making a strapped tube by the simple expedient of gouging away some of the anode to make room for the straps. They thought there would even be room for double strapping. The first of these 18-vane T tubes (T1, No. 1) was completed on July 22. In these tubes the straps stood up above the top of the crown. The tubes were strapped differently from the 3-cm tubes, because the pairs of straps are one above the other instead of side by side. The next step was to try a sharp vertical groove cut in the fins. These tubes, however, gave low power and low efficiency. The first good strapped tube was made in August 1943 and was of the type just described. This tube gave a peak power of 25 kw, an efficiency of 28.2 per cent, and a wavelength of 1.628. It was some time before a tube was made that could duplicate these results. All told about 15 experimental tubes were built using different types of strapping (with shorter rings, or with rings of somewhat different shape, or somewhat differently attached to the vanes).

Radial Strapped-Tube Design

About the beginning of 1944 radial strapping was adopted. Straps of this sort are easier to space and to inspect. A special jig was devised to facilitate assembly. Tubes of this series (the F or RF series as they were called at Columbia) gave efficiencies of nearly 30 per cent and power of the order of 50 kw. These tubes were double-strapped, and though the wavelengths (having been raised as is usually the case as a result of the strapping process) were still too high, it was hoped to bring the wavelengths down to 1.25 cm.

The first anode blocks were made by casting a copper-gold alloy in a steel mold which was then dissolved away by acid. The later crowns (as they are called here) were done by the hobbing process. In order to prepare them to receive the straps the crowns were filled with Lucite and the concavities milled into the vanes. The Lucite was then dissolved out with chloroform. The straps were silver-plated and soldered to the vanes by heating in hydrogen.

4.2.4 The Rising Sun Magnetron (A Tube)

The chief rival of the strapped 1-cm tube, and one of the most important developments of CUDWR-RL, is the tube which had been developed to operate in the π mode, yet without strapping.

The original impulse leading to the development of this magnetron came from an interchange of ideas between Nordsieck and Millman in the early spring of 1943. It was Nordsieck's original suggestion that asymmetries might be introduced in the tube by means of bumps or grooves made in certain of the resonant cavities. By this means, if it could be found out how to do it successfully, it should be possible to imitate the effect of strapping. On rather intuitive considerations it was felt that if on a 12-vane or 15-vane tube the bumps or grooves were placed regularly around the tube certain desired modes could be encouraged and others suppressed. A cold test was made on a 10-cm model of a 12-vane tube and it was proposed on April 7, 1943 that a 15-vane tube be made. A 15-vane tube was first built, with grooves cut in every fifth sector. It was tested on April 12. Data were taken that enabled them to plot curves of wavelength in centimeters against the depth of the cut in inches. Tests were made on a 12-vane model. The results were very poor.

It was then proposed to try the effects of a double slot, which would give further additional inductance. This was tried on a model of a 12-vane and then a 15-vane tube. In this case they got poor results, that is, poorer mode separation than with a single groove.

At this point Nordsieck sat down and tried to make calculations on the basis of transmission line theory, computing the ratio of the wavelengths for a cut and uncut cavity. He found that he could predict the results that had been obtained with the 16-vane tube. One afternoon at the end of June or early in July Nordsieck and Millman evolved the idea of cutting alternate cavities. Nordsieck then proceeded to work out the theory for this case, but they were so confident that their idea was correct that they began experiments a day before the theory was finished. They made a scaled-up model with 14 resonators, every alternate one being cut. It was tested for the first time on the weekend of July 11, 1943.

On the strength of the cold test bench results they made a couple of tubes, but they were extremely bad. Somewhat discouraged, they resolved to put the matter on the shelf for a while. Later they got the apparently simple idea of cutting the grooves more deeply, which led to the final success. The tube that resulted has been called the Rising Sun or the A-tube.

The race was now on between the Rising Sun and the strapped tube. The Navy placed an order with Western Electric for 10,000 1-cm tubes yet to be developed. A meeting was held on April 25, 1944 and it was decided that BTL should begin work on the Rising Sun.

4.2.5 The Tunable 3-cm Magnetron

The work of CUDWR-RL received a distinct impetus as a result of the decisions that were taken in the late spring of 1943 in the conferences held in London between the British and the members of the visiting United States special mission on radar. At the meetings of May 18 and May 19, 1943, between the Compton mission and the radar board working committee it was decided that the British should abandon all fundamental work on 3-cm components to the United

States, but continue, in parallel with the United States, to do work on experimental 3-cm systems. America was to provide 3-cm magnetrons for the systems development work on both sides of the Atlantic. At the same time it was agreed that the development of tunable magnetrons, which the British were stressing in the hope that they would provide immunity to jamming, would be entirely entrusted to the United States.

After the return of the Compton mission to this country in June, a number of conferences, formal and informal, were held involving members of the MIT-RL, the Armed Services, CUDWR-RL, and BTL. At one of these meetings held at MIT-RL it was agreed (since Rabi had sounded out the Columbia staff about it a few days before) that the BTL and CUWDR-RL should work closely together on the tunable 3-cm magnetron. Columbia then made plans to divide its staff, keeping part of it at its 1-cm work, but shifting another part to work on the problem of the tunable 3-cm tube.

Available Data on Tunable Magnetrons

At this time the tunable 10-cm magnetron, as contrasted to the tunable 3-cm, was well over a year old. The first tunable 10-cm, where tuning is effected by mechanical deformation of the magnetron cavity, is quite generally credited to Percy Spencer of the Raytheon Company. The earliest such magnetron brought to the attention of the MIT-RL magnetron group was one they saw in operation during the winter of 1941-42 in the Raytheon preproduction SG radar set at Deer Island, in Boston Harbor. Tubes of this sort were submitted by Raytheon and were tested by the MIT-RL during the spring and summer of 1942. A number of the important mechanical features which have made the magnetron dependably operable, such for example as the idea of using ballbearings with a sylphon, were suggested by MIT-RL.

Experimental Design

Mechanical deformation of the sort used on 3-cm did not appear feasible with the smaller magnetrons. Both CUDWR-RL and BTL experimented with tuning by means of plungers and pins inserted into the resonant cavities. BTL, largely under J. C. Slater's inspiration, experimented with asymmetrical tuning of this sort, whereas Columbia, in the manner that will be shortly described, had great success with a symmetrical design. The BTL group, which was designing a finished tube for production at Western Electric, agreed to adopt almost without change the electric features of the tube designed by P. Kusch of Columbia and known as the "Crown of Thorns."

Development of "Crown of Thorns"

The Crown of Thorns was essentially a packaged 725 (a 3.3-cm tube of the hole and slot type). Tuning was accomplished by inserting a set of metallic pins or plungers into all the resonant cavities. The possibility of tuning in this fashion was suggested at CUDWR-RL by Simon Sonkin, as a consequence of an earlier observation. He had used small glass rods inserted in the magnetron cavities, during cold resonance tests of a 1-cm magnetron, in order to distinguish the magnetron resonances from resonances in the line. Sonkin put this idea into effect (although after its use by Kusch on 3-cm) in making a 1-cm tunable. He completed the first of these on July 15, 1943.

CUDWR-RL Experimental L2 Tubes

Sonkin proposed a tuning structure with the structure supporting the pins between the magnet pole pieces and the anode segments. It was Kusch's suggestion in June 1943 that one could get a more efficient mechanical design and conserve space by putting the supporting structure within the pole pieces. His first operating tube was completed July 10, 1943. This tube, which he called the L1, worked, although not well; but it served to demonstrate the general validity of the scheme.

Three tubes, called L2 tubes by the Columbia workers, demonstrated the possibility of using a short gap between the built-in pole pieces of the magnet.

Kusch reported these results at a conference held at BTL in New York on August 17, 1943. At this meeting representatives of CUDWR-RL, BTL, Westinghouse and MIT-RL were all present. Kusch reported that his tube gave 8 to 10 per cent tuning and an efficiency of about 45 per cent at the ends of the tuning range and 30 per cent at the dip in the curve. Fisk of BTL reported that his use of

a single plug in one resonant element gave roughly a 2.5 per cent tuning range over which the power remained roughly constant. The frequency shift was not linear with the displacement of the plug. The Columbia group expressed confidence that the minimum observable in their own tube could be removed. After some discussion it was agreed to push a tunable magnetron for the XL band, that from 3.53 to 3.33 cm, for this had first priority among the requests of the combined communications board. It was agreed at a later meeting to concentrate on the Columbia type of tuning device.

Development of L-Series Tubes

In consequence CUDWR-RL ordered special anodes from the BTL, slightly modified from the 725A design, and intended for 3.5-cm tubes that would tune over the XL band. Since it was clear that the minimum in the power-wavelength curve resulted from the electrical properties of the magnetron end space, Kusch decided to change the resonant frequencies of the end space and, if possible, shift the minimum out beyond the tuning range.

L3 Series. The first step was taken with a tube designated as the L3-3 tube, in which a simple ring was inserted in the end space to cut down its area and its inductance. In the next tube, L3-4, it was decided to extend this as a collar around the plunger. This tube was tested on September 21, 1943, and was found to have a limited tuning range. The next two tubes, L3-5 and L3-6, were exactly like the previous ones except that the pins were larger, and consequently increased the tuning range, giving more megacycles per mil. These were tested on September 24 and September 22 respectively; and it was found that, for the first time, tubes were at hand which could cover both the XL and XS bands, that is the region from 3.13 to 3.53 cm. Kusch felt that, with these tubes, the problem was now well in hand. He and his co-workers accordingly made another 25 tubes.

L4 Series. The first series, L4, was intended for experimental use at MIT-RL. These were based on the 3.3-cm anode. Eight of these tubes were made, and of these five were satisfactory. They were designed between August 12-19, and the first tubes were tested in mid-October. They showed good tuning behavior, tuning over the range from 3.35 to 3.10 cm.

L5 and L6 Series. A series of L5 tubes was designed and projected but never made. Tubes of a still different design made up the L6 series. The size of the end space was slightly altered to adapt the tube to another type of magnet; and these tubes had 11 tuning pins in a 12-resonator tube, thereby demonstrating the possibility of reducing the number of pins without greatly distorting the tuning curve. Three of these tubes were made. At this point Kusch altered the shape of the collar, giving it a 45° angle at the wall in order to compensate for the increased capacity due to the greater size of the tuning pins. This improvement was introduced into tube L6-3, which was tested for the first time October 22, 1943.

L7 Series. Two tubes of the L7 type were made in which the gap length was reduced still further (from 0.400 in. to 0.370 in., the dimension finally adopted) with consequent saving in magnet size. The tubes were both tested in mid-November 1943 and were found satisfactory. At this point in the development, during the design of the L7 tubes, BTL entered the picture and tried to make their first tubes. The first designs were not very satisfactory. Up to this point BTL had supplied the anodes and the 725A output circuits and had been seeking to improve the latter.

L8 Series. The L8 magnetrons were designed collaboratively by Kusch of Columbia and by the Bell engineers. The objective was to design a magnetron on sound mechanical principles that would be interchangeable mechanically and electrically with the 725. A decision had to be made as to whether it was to be a Rising Sun or a strapped magnetron. Although strapping would be a more conservative approach, it would mean an increase in mechanical difficulties. It was decided to use the Rising Sun design. Bell was assigned the problem of developing a satisfactory magnet, subject to the limitation that it be interchangeable with the magnet of the 725. Bell's first magnet design was much too large and cumbersome and brought criticism on this score from both Rabi and Kellogg who went to Bell to register their disapproval. The Columbia workers then approached the Indiana Steel Company, which had made magnets successfully for MIT-

RL. This company brought forth a good design which was submitted to the Bell people.

FINAL DESIGN AND PRODUCTION

On March 6, 1944, Fisk, Hagstrom, and Glass of Bell met Kusch and Nordsieck of CUDWR-RL at the Pupin laboratories and held a conference in which they thrashed out for the first time the elements of good mechanical design. On the basis of decisions made at this conference Bell went ahead with the design of the tube. The problem of production was turned over to the Chicago plant of Western Electric Company, but by the time the tube reached that stage the war was at an end.

The other tube problem on which CUDWR-RL made a major contribution was the improved E-5. It had been a strapped magnetron. It was decided to convert it to a Rising Sun. This decision was made in sufficient time to allow for redesign and production by Sylvania. By war's end several thousand tubes had been delivered by Sylvania.

In its research in high-frequency tubes CUDWR-RL made one other contribution, this in the field of propagation studies during the last year of the war. CUDWR-RL determined experimentally the position of the water absorption band. To do this tubes were built which operated in the vicinity of 0.9 cm, and a magnetron was developed which would operate on a wavelength of 3.5 mm.

Chapter 5

SELECTED GROUND SYSTEMS PROJECTS

5.1 HIGH-POWER RADAR FOR GROUND CONTROL OF INTERCEPTION, SCR-615

In the spring of 1941, MIT-RL sent one of its section leaders, K. T. Bainbridge, to Great Britain to study the British radar development. He returned deeply impressed with the importance of long-range early-warning systems, and especially with the lack of suitable height-finding provisions. In mid-September, a group was founded at MIT-RL under his direction to explore the possibilities of high-power radar (which then meant radar handling any peak power well in excess of 100 kw) and to design a set with height-finding features to serve as a *ground control of interception* [GCI] and under certain conditions as a low-coverage general warning set. Stimulated by the needs of the AIA program, the group working on the problem of high-power radar devoted its attention first to developing a shipboard installation for carriers to be used in controlling AIA-equipped night fighters.

5.1.1 Requirements of High-Power Radar

It was hoped that magnetrons would be forthcoming on 10 cm that would give powers in the neighborhood of 500 kw. The use of high-power modulators and of large paraboloids, 6 to 10 ft in diameter, seemed to be the other principal requirements. Since coaxial transmission line would be subject to breakdown at these higher power levels, a 10-cm waveguide was designed along the lines that the advanced development section had worked out for 3 cm.

5.1.2 Design Developments

EXPERIMENTAL CXBL SYSTEM

An experimental roof system was put into operation in the first week of February 1942. During the next few months it was resolved to incorporate two important features: (1) conical scanning for precise positioning in elevation and azimuth, and (2) the instantaneous presentation of height. Since the height of the target is given by multiplying the slant range to a target by the sine of the elevation angle of the antenna, electric circuits were designed which performed this computation automatically so that height, corrected for the effect of the earth's curvature, would be read directly and continuously on a meter.

The roof system was successfully tested as a GCI system against the laboratory B-18 plane on May 15, 1942. In the spring of 1942 preliminary specifications for the shipboard set, the SM, were completed in conference with U. S. Navy representatives, and a letter of intent was given GE for manufacture of the equipment. Work was begun on a prototype, called the CXBL, to be produced at MIT-RL. Meanwhile in July an experimental system was set up at a field station on Beavertail Point, Jamestown, Rhode Island. Because of the proximity of the Naval Air Station at Quonset it was possible to test this new type of system against U. S. naval aircraft. The installation was also used to try out components and design features of the CXBL. The CXBL equipment was completed and installed before the end of March 1943 on CV-16, the USS *Lexington*. This experimental unit had extensive operational use in the Pacific before it was replaced by production equipment.

EXPERIMENTAL SCR-615 MODEL

The parallel development went forward to produce a GCI set for the Army designated SCR-615. An experimental prototype was sent to the Army Air Force School of Applied Tactics [AAFSAT], Orlando, Florida, where it was tested late in 1942. Another was installed at Panama, as part of the Caribbean defense system, early in 1943. Still another laboratory-built set was sent to England in the early spring of 1943 where it was set up for testing at Worth Matravers. Prototypes were also delivered to Camp Evans Signal Laboratory, Belmar, New Jersey, and to the Westinghouse Electric and Manufacturing Company which was elected to produce the SCR-615. The production units began to appear in the summer of 1943. About one

hundred were produced in the next two years.

The SCR-615 was not widely used or thoroughly satisfactory as a GCI set, in fact it did not see extensive service even as a warning device. The set was extremely complicated and difficult to maintain, though this was somewhat less true of later models. One unit was used by the British Admiralty at Dover Castle for early warning. Two sets in mobile form were sent to France, where at least one of them was used as a height-finding set with an MEW installation. Two sets served in Corsica, one at Cap Corse with an MEW which covered the invasion of southern France, another at Ajaccio where it was used as a GCI set and reportedly was successful in bringing down a JU-88. A few sets found their way to the Pacific.

5.2 MICROWAVE EARLY WARNING [MEW], AN/CPS-1

5.2.1 Early Developments

As a high-power set for early warning, a function for which it had not been primarily designed, the SCR-615 was soon outclassed by a now illustrious set for *microwave early warning* [MEW], which has received the joint Army-Navy designation of AN/CPS-1. MEW was an independent outgrowth of the same interest in high-power sets which had given birth to the SCR-615. In particular, the set was conceived during the months immediately following the Pearl Harbor attack when it appeared likely that a powerful early-warning system might well be needed to protect the West Coast against Japanese air assault or even invasion.

Requirements of MEW

A careful study was made of the conditions which such an early-warning device should satisfy in order to give adequate protection, due regard being paid to the speeds of attacking bombers and the rates of climb of defending fighters. It was determined that the beam should reach an altitude of 40,000 ft at 200 miles. To produce this coverage it turned out that a fan beam 3 degrees wide in the vertical plane and extremely narrow in the horizontal plane was desirable; while the beam was narrow enough in the vertical plane to give low coverage its breadth enabled it to sweep the sky without recourse to complicated scanning. The high gain required in the horizontal plane in order to attain the desired range gave the set the incidental benefit of extremely high resolution. The MEW project took form at MIT-RL when in the spring of 1942 it was decided to produce the fan beam by means of a linear array antenna which was being simultaneously considered as a means of producing a high-gain antenna for bombing purposes.

MEW Antenna. The first antenna planned for the MEW system was to be a so-called leaky pipe linear array in which a succession of holes cut in a waveguide served as the sources of radiation. This was soon replaced by a linear array consisting of a row of dipoles to which energy was fed by means of probes inserted into a length of waveguide. The use of probes allowed the pattern of radiation to be adjusted as required. The linear array was backed by a cylindrical parabolic reflector.

First MEW Installation. The first MEW system was assembled in the late summer of 1942 and installed in a special structure, resembling a gigantic radome, raised above the second level of the penthouse of MIT-RL Building 6. The r-f parts of the equipment were mounted all together back of the reflector, while the indicators, the power supply, and high power Link modulator were in a room underneath. The linear array was 16 ft long; the reflector, 16 ft long and 10 ft wide.

5.2.2 Critical Development Problems

Power Requirement Problems

Many of the characteristic features of MEW resulted from the necessity of handling large amounts of power, for it was hoped that a system could be designed to give a megawatt (10^6 w) of pulse power. The "back-of-dish" design is a case in point, for it made it unnecessary to carry r-f power over long distances. Waveguide, which the earlier group working on high power had introduced for 10 cm, was even more important at the high power levels envisaged for MEW, for though coaxial line might have carried a few hundred kilowatts without arcing, waveguide could carry ten times that amount. The extremely high power levels gave rise to problems that had not been encountered, or at least not in such

critical form, with low-power systems. Arcing of the magnetron input feed and serious crystal burnout were the most persistent problems. The latter was due to the unsuspected strength of one harmonic of the radiation frequency which leaked through the TR box and injured the crystal. The development of a special crystal mixer with a choke to eliminate this harmonic was a necessary and important step.

Indicator Problems

Flight Test Results. During the fall of 1942 MEW was flight tested almost daily against U. S. Army and U. S. Navy aircraft flown from the East Boston Airport. It had not been clear at first what indicators would be required. These tests showed that the original indicators, planned before the MEW was actually put in operation, were inadequate to handle the unexpectedly large amount of information the set provided. As a result of these tests an indicator system was adopted that consisted of an A-scope, a B-scope, and two 7-in. PPI's with ranges out to 200 miles. The flight testing also verified the theoretical shape of the beam and revealed the need for an auxiliary antenna to provide high-level coverage close to the station. It also resulted in altering the dimensions of the principal reflector.

Result of Increasing Installation Elevation. In the spring of 1943 a second MEW was set up on a 100-ft tower at a site on the Gulf Coast of Florida near Orlando. In this system the power output of the magnetron was more than doubled, which revived the problem of crystal burnout and required a careful redesign of the dipoles. The set was supplied with two 12-in. PPI's, one to handle the signals from the principal beam, the other for the auxiliary gap-filling beam; and there were in addition three B scopes and a particularly flexible precision indicator called a "micro-B." The greater range resulting from the elevation of the installation, the higher output power, the longer array (i.e., with higher gain) caused the main beam to fill to capacity the indicators that had been intended for both beams.

The extraordinary traffic handling capacity of the MEW made a great impression upon the Army officers at AAFSAT. Using existing radar equipment it had been customary to report all isolated information to AAFSAT filter center; but with the advent of the MEW, which on certain days could have reported as many as 12,000 plots, the filter center would have been jammed with information telephoned in from the MEW site. A system of "prefiltering" the tracks, at the MEW site, that is, sending on only clearly defined tracks to the filter center, was evolved to avoid clogging the center.

5.2.3 Practical Applications of Experimental Models

Experimental Experience

Under the supervision of Col. T. J. Cody, head of the Air Warning Department of AAFSAT and a member of the Air Forces Board, rigorous tests were carried out during the summer and fall of 1943 to test the potentialities of the system. The conclusions were uniformly favorable and Colonel Cody satisfactorily confirmed his own first impression that the Air Forces had "hit the jackpot." The new and extremely powerful radar was readily adapted to Air Forces thinking which had already decisively shifted to the offensive; at AAFSAT considerable thought was paid to the possible uses of MEW as a control instrument in aerial offensive warfare, and the result was a campaign, in which Cody was a ringleader, to have the MEW designed so that it could be made mobile.

The manufacture of 100 MEW sets based on the MIT-RL prototype at Tarpon Springs, Florida, was entrusted to GE in the early summer of 1943. MIT-RL was to serve as consultant. At a conference held in General McClelland's office in the Pentagon in August 1943 it was agreed that the production sets would probably not be available before early 1945 and that operational experience with the equipment was urgently needed. The laboratory agreed to build a total of five MEW sets on a crash basis (this was later increased to seven), one to go to England for the use of the Eighth Air Force, the rest to go to the Southwest Pacific, the Central Pacific, and the Aleutians for use in training.

Field Operations

Of the seven preproduction MEW's for overseas use, only one finally was sent to the Pacific,

where it was installed on Mt. Tapolchau on Saipan in January 1945, and served both as a defensive warning system and to keep track of homecoming B-29 raiders. The crews of at least two downed B-29's and one P-38 were rescued as a result of information from the MEW.

British Experience. The second MEW produced, set up at Start Point, Devon, in January 1944, was the first of the crash units to reach a theater of operation. The site was suggested by the British to complete a chain of Type 16 stations they had set up at Dover, Ventnor, and Beachy Head. The Start Point station, serving both as a training station and an operation unit, was manned jointly by British and American personnel, and aided by a British Type 24 height-finder worked with Eleventh Fighter Group RAF in controlling offensive fighter sweeps against the Continent.

It was here that the true power of MEW as an aircraft control center first was clearly demonstrated. Many changes in equipment and in mode of operation were made before the set could function as a self-contained control station. These innovations, among them the use of a vertical glass screen for plotting, and the use by the controllers of "off-center" PPI's (designed at BBRL), were adopted for later sets.

During the D-Day operations, the night of June 5-6, 1944, the Start Point MEW performed three types of supporting operations. The first and most continuous was maintaining a patrol of Thunderbolts flying off the Brest peninsula. A second job was sending fighter bombers over various targets. A third was aid in the rescue of pilots downed in the channel. The MEW control room provided a grandstand seat for following the aerial assault upon the Normandy beachhead. Shortly after D-Day, this MEW, handed over to the 19th TAC, Ninth Air Force, was made mobile and was used with great success to track the V-1 flying bombs. Later it was sent to the Continent.

Mediterranean Experience. In the meantime, the first crash model of MEW, which had remained in Florida for training purposes, was removed at the request of the Air Forces and taken to the Mediterranean Theater, where it was installed in May 1944 on a northernmost headland of Cap Corse on the island of Corsica. This station remained in operation until the end of August, and afforded a view of the air activities of the invasion of southern France on August 15 comparable to its companion in England on D-Day in Normandy.

Mobile System in Continental Operations. The third MEW produced was made mobile directly upon arriving in England in the spring of 1944 and crossed the Channel to France on D-Day plus 6. Located at a point called Greyfriars on the East Coast of England from June to October 1944, the fifth MEW was assigned to the Eighth Air Force to follow bombing missions also, with the help of the height-finding Type 24, to rendezvous planes, control fighter escorts, and direct fighter sweeps against enemy airfields in advance of the bomber stream. In October, the Eighth Air Force decided that the set would be more useful nearer its targets. It was made mobile and shipped to Holland and assigned full responsibility for control of all Eighth Air Force fighter missions over the Continent.

5.3 FIRE-CONTROL RADAR FOR SHORE BATTERIES, SCR-598 OR AN/MPG-1

5.3.1 Requirements and Characteristics

NEED FOR RADAR IN COASTAL DEFENSE

In 1941 the Coast Artillery Board, after several years of study, found that the coast defenses of the United States against motor torpedo boat attack were inadequate. The development of the 90-mm gun M1, of gun data computer T-13 for the 90-mm gun, and of gun data computer M8 for 6-in. and 8-in. harbor defense batteries were initiated. In May 1942, motor torpedo boat attacks on our harbors were considered a possibility and while there was an excellent general surveillance set, the SCR-682, there was no radar equipment to detect and track small and highly maneuverable craft.

After conversations with MIT-RL representatives from May to July, Col. W. B. Bowen, President of the Coast Artillery Board, in a letter to the Chief of Ground Requirements Section, on August 3, 1942, proposed military characteristics for a radar to replace SCR-296, designed for installation in the Battery Commander's Station of an emplacement for 90-mm anti-motor torpedo

boat guns. He also recommended that RL be requested to design and develop the radar unit. on September 2, 1942 the laboratory received the request for a pilot model designated SCR-598.

The resulting system was the most effective fire-control radar for seacoast artillery in operation at the end of the war and one of the most unique 3-cm systems to come out of MIT-RL research and development.

The high accuracy of the guns to be controlled and the requirement of handling 70-knot boats at 500-yd range determined certain design features. A beam narrow in azimuth and with low side lobes and the use of a 0.25-msec pulse were necessary to give the resolution and angular discrimination required.

Design Features of SCR-598

Antenna and R-F System. The most original feature of SCR-598 is the antenna and r-f system. Optical mirror theory solved the antenna problem. For this reason the antenna is called a "Schwarzschild" since its geometry is derived from the Schwarzschild astronomical telescope. The radiator is a folded, sectoral horn. Sectors of the folded waveguide are equivalent to the diametrical sections of mirrors in the optical system which was used as a guide in design. In operation r-f energy is fed into a folded piece of waveguide from a horn which scans in the horizontal plane. A plane wave 0°.6 wide, swept through 10° in azimuth and sweeping 16 times per second, is produced. For search the scanning system is stopped and the entire antenna is rotated through 360°. The antenna assembly is housed in a plywood shell (called from its shape the "bathtub") which is supported on a pedestal similar to the one used for SCR-584.

Indicator Designs. Several indicators are provided. For search there is a 7-in. PPI with two scales, 30,000 and 80,000 yd. For these, continuous or sector scan may be used. The 7-in. B scope presents an expanded version of a section of the PPI and covers an area 2,000 yd deep and 10° wide and may be centered anywhere within the tracking range of the set. A second B scope is provided for shell-spotting which makes it possible to read range and azimuth deviations from the center of impact so that after correction future rounds may fall directly on the target.

5.3.2 Development and Performance of AN/TBG-1 and AN/FPG-1

The MIT-RL prototype was assembled in mobile form and after five days of testing around Boston Harbor it was shipped to Fort Story, Virginia, in November 1943. Firing tests which were spectacularly successful were carried out in the presence of U. S. Army and British observers. The mean tracking error was found to be 5 yd in range and 0°.03 in azimuth. In convoys large ships such as carriers could be distinguished from smaller craft such as destroyers and even PT boats.

The Bendix Radio Division of Towson, Maryland, had been called in to prepare for production and had sent engineers to the laboratory to follow the development in February 1943. At the end of the year, however, the military situation had changed to the offensive and it was thought no longer necessary to produce the fixed installation. Therefore the SCR-598 became the transportable AN/TPG-1 for use with mobile seacoast artillery and at the request of the Marine Corps the mobile version AN/MPG-1 was ordered. The fixed version AN/FPG-1 was at first abandoned and later reactivated when it was planned to install the equipment at fixed harbor defense batteries in Hawaii, Panama, and Alaska.

In the spring of 1944 MIT-RL agreed to send the prototype SCR-598 to the Pacific for tests at Oahu and to furnish personnel to install and operate it there. Extensive demonstrations were carried out with 90-mm, 155-mm, 12-in., and 16-in. batteries. With a locally trained crew average tracking and spotting accuracies were found to be about 0°.05 in azimuth and 10 yd in range. Ships could be distinguished as separate targets when separated by only 50 yd. Splashes from 155-mm shells could be spotted at ranges out to 28,000 yd.

After these tests SCR-598 was transported to Iwo Jima where it arrived on April 25, 1945. Some time was taken in arranging for a semipermanent site so the set was not turned on until May 2, 1945. Although the AN/MPG-1 was in production and several sets had been shipped to the Pacific by V-J Day the MIT-RL set was the first and only one to see service in a combat area.

5.4 BEAVERTAIL HEIGHT-FINDER, AN/CPS-4

5.4.1 Report of Ad Hoc Committee

Early in 1943 E. L. Bowles, expert consultant to the Secretary of War, set up an ad hoc committee, headed by J. A. Stratton of his office, to review and make recommendations regarding the then chaotic state of the U. S. Army ground radar program. The committee submitted its report in the summer of 1943; it was accepted by the U. S. Army and resulted in a sharp curtailment of its radar program.

5.4.2 Development of AN/CPS-5 Equipment

Nevertheless, the report encouraged the development of a 10-cm height-finding set to be used with the AN/CPS-5, a 1,200-cm search set. This became known in the laboratory, because of the shape of the beam it produced, as Beavertail. It was officially designated AN/CPS-4. The Signal Corps asked the laboratory to be consultants on this development, with the Federal Radio and Telephone Corporation (at that time, the intended manufacturers of the equipment) acting as the designers. By December 1943, however, Federal had dropped from the picture, partly because of the plant expansion which the company said was required to build 200 models, partly because of the company's unwillingness to guarantee delivery dates. GE, already the manufacturer of the CPS-5 equipment, took over in early 1944 and received a contract for 100 models, with MIT-RL as consultants.

Antenna and Indicator Design

It was chosen to design an antenna narrow enough in the vertical plane to permit direct reading of height from the angle of the antenna. The CPS-4 antenna was horn fed with a reflector 20x5 ft shaped as an elliptical section of a paraboloid. The antenna gave a beam 1.2° wide in the vertical plane, and to pick up the targets in altitude this was raised and lowered 25 cycles per minute by nodding the antenna structure. This was a height-finding principle favored by the British. Signals were displayed on a special indicator which plotted elevation angle against range (out to 90 miles) a[illegible]ut out ground clutter except for the baseline of the scope.

Test Performance

In April 1944 a laboratory-built, experimental CPS-4 was set up at Bedford Airport to check general performance, height accuracies, and range. Height accuracy tests showed better than ±1,000 ft at 60 miles. By May a final draft of specifications had been given to GE, and a production schedule had been set up which called for first deliveries in May 1945. In August, the Bedford model moved to Leesburg, Florida, for operational tests in conjunction with the V-beam equipment, under the direction of the Orlando Army Air Forces Board. These tests indicated height errors of the order of ±300 ft. An average of 3.6 sec was required to fix the height of a target, once its range and azimuth had been obtained from the associated search set.

The first production model CPS-4 came out in June 1945. Several CPS-4 sets were shipped to the Pacific during July and August, but none arrived in time for combat.

5.5 V-BEAM, AN/CPS-6, RADAR FOR EARLY WARNING, ACCURATE HEIGHT-FINDING, AND TRAFFIC CONTROL

5.5.1 Specifications and Characteristics

On March 20, 1943, the steering committee of the laboratory approved a project suggested by the Army for a *portable ground control of interception* [PGC] set to give wide coverage and great raid handling capacity as well as rapid and accurate height-finding. According to the Army specifications, readings of height were to be supplied every 10 sec with an accuracy of 500 ft.

After several months of canvassing the possibilities of separate search and height-finding systems, the laboratory began the design of a single system operating on 10 cm to answer both requirements. The so-called V-beam system, AN/CPS-6, the laboratory name of which was derived from its double beam, used an antenna system larger than that of any other American radar, consisting of one antenna giving a vertical fan beam for search and a second "slant" antenna giving a beam at an angle of 45° from the other. The range of the search beam was about 200 miles; the auxiliary antenna used conjointly with the other in height-finding was useful out to about 140 miles. Height-finding depended

upon the fact that as the two beams scanned simultaneously a target was picked up first by the vertical beam and then by the slant beam, and the time difference depended only upon the slant range to the target and the height of the target.

These antennas had multiple-horn feeds, providing energy from a total of five magnetrons, and produced fan beams 1° wide in azimuth for fine resolution and 30° in elevation for all-altitude coverage. In addition to PPI's and B-scope, the V-beam system used a special height indicator which displayed the returning signals from both beams so that height could be read directly.

5.5.2 Production and Testing

The first laboratory V-beam system, in operation by February 1944 at the Bedford Army Airport, had all its components except indicators mounted on an old carnival merry-go-round modified into a radar mount, the whole having the aspect of a giant back-of-dish installation. Tests at Bedford were so promising that the system was moved to Leesburg, Florida, for tests by the Army Air Forces Board during which the set demonstrated its ability to see through large quantities of "Window" in April 1944. On the basis of the satisfactory Florida tests, the Signal Corps officially requested MIT-RL to build 6 preproduction models of the V-beam or AN/CPS-6, and this order was later increased to 8. The Stone and Webster Company was given a contract to design a suitable mount. The mounts were manufactured according to this design by the Walsh Construction Company of Boston.

The first mount was set up in a stockade near MIT Building 20 in December 1944. After a search of the Boston area to find a satisfactory site for erecting these large systems, it was determined to establish an Orlando Field Station of MIT-RL at Orlando, Florida, in January 1945. The first preproduction V-beam system was in operation from a 25-ft tower at the Orlando Field Station in March 1945. By October 1945, 5 of the 8 sets had been completed—3 stayed in this country for training purposes, 1 was shipped to the Pacific area and 1 to the Panama Canal Zone. In December 1944 a contract was let to GE by the Army for 60 production V-beam sets.

5.6 LIGHTWEIGHT HEIGHT-FINDING RADAR, AN/TPS-10

The AN/TPS-10 project (MIT-RL "Little Abner") filled the need for a lightweight radar which could be carried into mountainous country and be used to detect low-flying planes. In the laboratory, the TPS-10 was considered more as a detecting device than as a pure height-finder. In this light it was expected, as far as low-flying planes were concerned, to be a stop-gap for the slower moving program of the *moving target indicator* [MTI], a special attachment which was designed to wipe out ground clutter and present only the signals from moving targets on the indicator. MTI will be discussed later. Tactically, the TPS-10 was thought of in terms of experience in the Italian Theater in late 1943 and in terms of experience in the Chinese and Burma Theaters.

5.6.1 Design and Development

DESIGN CHARACTERISTICS

The TPS-10 set was designed to be broken down for hand-transport (with a few exceptions, no piece weighed more than 40 lb) and to produce (at 3 cm) a flattened pencil beam 0.7° in elevation for height discrimination and 2° in azimuth. The beam "nodded" rapidly in elevation while scanning slowly in azimuth. The TPS-10 overcame the difficulty of ground clutter on the scope by using a single range-height indicator (adapted from the MIT-RL Beavertail indicator) which plotted elevation angle against range, thereby restricting clutter to the baseline of the scope.

TESTS OF EXPERIMENTAL MODELS

The project was undertaken in the winter of 1943-44. An experimental laboratory TPS-10, assembled from available components, was tested at Bedford Airport by April 1944. Ranges were short (of the order of 30 miles) due partly to the low power of the modulator and partly to low receiver sensitivity. The tests indicated, however, that with certain improvements ranges would be satisfactory. Between April and June, these chief improvements were made: electrically, a higher power modulator (borrowed from the H_2K) and a more sensitive receiver (SO-SU type); mechanically, a new reflector and new elevation and azimuth movements. In July, this

improved Bedford model was moved to North Carolina for tests in hilly country. These tests, which were witnessed by representatives of the Army Air Forces and the Signal Corps, indicated that a medium bomber could be tracked at ranges of 40 to 50 miles with approximately 50 per cent success and that target discrimination was possible where the target was separated from the ground by at least one beam width.

Application

On the basis of the North Carolina tests, the Army asked the laboratory to build 40 sets, to be preceded by 2 prototypes. The first of these was operationally tested by the AAFB at Leesburg, Florida, in November 1944, both separately and (for GCI) in conjunction with the AN/TPS-1, a portable U. S. Army search set. The second prototype, TPS-10, was tested mechanically at East Boston Airport and then sent to Warner-Robins Field, Georgia, where it was used for training Army personnel. Production of the 40 sets covered the period from January to June 1945, with the manufacturing being done in the laboratory by officers and enlisted personnel who were later assigned to the sets. Besides being used for training in the United States, TPS-10's went to France, Italy, Saipan, Iwo Jima, and the CBI Theater.

In February 1945, a letter of intent for 100 sets (increased in April to 150) was given to the Zenith Radio Corporation, delivery to start in June 1945.

Chapter 6

AIRCRAFT RADAR SYSTEMS

6.1 AIRCRAFT LANDING SYSTEMS, PGP AND GCA

6.1.1 Origin of Theoretical Principles

REPORTS FROM ENGLAND of work on jamming, beacons and blind landing resulted in the creation of a group at MIT-RL, under the direction of Luis W. Alvarez, to study these problems. The group began to lay out a blind-landing program in September 1941. The accidental discovery that the experimental prototype of the SCR-584 had twice been observed to follow airplanes all the way into a landing suggested the use of radar for blind landing. Alvarez had been following the preliminary experiments of the precision gunlaying group and conceived the idea that the directional properties of the conical beam might be used to define a straight-line path down which an airplane might fly. If the gunlaying equipment could be used, the only remaining problem was to devise a scheme by which the pilot could be given information of the magnitude and direction of his deviation from the predetermined glide path.

6.1.2 Types of Systems Devised

Two contrasting systems were ultimately devised. One resembled, in general outlines, the early MIT-RL continuous-wave system, but using a pulsed glide path, required receiving apparatus in the aircraft. The other, a "talk down" system, requiring no special gear in the aircraft except its normal communications system, was subsequently used in the *ground-control of approach* [GCA] radar. If, it was argued, a ground operator could tell so easily by radar the precise location of an incoming plane, why would it not be possible to convey this information to the pilot by radio telephone?

6.2 PULSE-GLIDE-PATH SYSTEM

6.2.1 Preliminary Experiments

The first scheme explored was the *pulse-glide-path* [PGP] system; and it was decided to test a rather simple version while waiting for the XT-1 radar (a piece of equipment then much in demand) to be available for blind-landing tests. The ground transmitting system used a horizontal 10-cm dipole which was nutated through a 3-in. circle about the focus of a 48-in. paraboloid. The conical beam thus produced was divided into four distinguishable quadrants by switching the repetition rate every 90° by means of a mechanical commutator. The operation of the system was based on the fact that, in the receiver aboard the aircraft, pulse repetition rates could be discriminated from one another by the use of suitable audio-filters. The amplitude of the signal strength in the various quadrants was compared by means of a cross-pointer meter. The line of equal signal strength corresponded to the desired glide path for the aircraft. After preliminary experiments during November and December 1941, it was decided to use a 3-cm system and to install it in a truck for further tests.

6.2.2 Report of Ad Hoc Committee on Instrument Landing

Meanwhile the director of OSRD appointed Alfred L. Loomis as chairman of a committee known as the "Ad Hoc Committee on Instrument Landing" to study the military aspects of blind landing, to consider the future needs of the Services and to recommend programs of research and development. The committee was also directed to consider the British requirements.

The committee, consisting of Army and Navy representatives as well as NDRC members, held its first meeting on December 4, 1941, and issued its final report on February 16, 1942. Luis W. Alvarez and Donald E. Kerr of MIT-RL studied all existing blind-landing systems, British as well as American, and submitted a report which was edited by E. L. Bowles, Secretary of the Microwave Committee. The Ad Hoc Committee on Instrument Landing reported that the Army had found no solution for the instrument landing of fighter types of aircraft and that the Navy had no system in prospect for carrier landings. The Navy placed emphasis on the need for a uni-

fied system for all Services. The committee recommended that MIT-RL explore as intensively as possible the application of some GL "talk down" method of instrument landing since most aircraft could not be burdened with receivers. Also the laboratory was advised to continue the pulse-glide-path work to fulfill immediate Army requirements.

6.2.3 Tests of PGP System

By Army request the PGP system was demonstrated, in conjunction with two other systems, at Indianapolis, Dayton, and Pittsburgh, in the presence of representatives of the Army, Navy and the British Air Commission from September 15 through November 26, 1942. The outcome of these tests was . recommendation by the Army that the Sperry Gyroscope Company undertake production of a glide-path system based upon MIT-RL equipment, for it seemed that this might be produced sooner than any other. Sperry agreed to undertake the development and the laboratory's truck was sent to Garden City for study.

The laboratory had previously ordered some models of the PGP equipment from the Delco Radio Division of General Motors to serve as prototypes. The first Delco model was tested in East Boston from January 12 to February 5, 1943. The laboratory's participation in this project ceased with these tests. Because Sperry did not display marked interest in the system, and because the Army did not push the project with any enthusiasm, this equipment never reached production. In the meantime the possibilities of a talk down system were being explored and the blind-landing program eventually proceeded along these lines.

6.3 TALK DOWN SYSTEM (GCL)

6.3.1 Preliminary Investigation

In April 1942, the XT-1 truck was made available for blind-landing experiments. For about two months (April and May 1942) tests were carried out. The results were, on the whole, rather poor. The GL antenna, except under anomalous conditions, would not give low enough coverage to land airplanes. It was evident that a special radar must be designed if a talk down system were to be feasible. The solution to the problem came with the decision to use the linear-array antenna, recently invented for MEW, and the radar bombsight, Eagle. The landing project then started off in another guise as *ground-control landing* [GCL].

Mark I Experimental System

Components. By July 1942, an experimental system was set up at the East Boston Airport and designs were drawn up for two trucks to house the Mark I system. The antenna truck housed two 3-cm antennas of the "leaky-pipe" variety with cylindrical paraboloid reflectors. A vertical antenna scanned in elevation and fed a PPI. A horizontal antenna of the same variety scanned in elevation and fed another PPI. These scopes were later replaced by B-scopes. The power supply and r-f system took up the rest of the space. The control truck housed the indicators and operators, the communications equipment and a 10-cm PPI radar search system for traffic control. A "director" mechanism for indicating deviation of a plane from an ideal flight path was later added.

Functional Purposes. The equipment was designed to perform two functions. First, when one or more aircraft are to be landed the search radar can "stack" all but the one plane to be landed and keep the others circling in a traffic pattern about the field; second, the precision units provide the operators with continuous information as to the position of the plane and precise instructions are given to the pilot over the air-ground communications system so that he is "talked down" to a point which is in line with the runway. No extra equipment has to be carried in the airplane.

Performance of Experimental Models

While improvements in the Mark I system, to make it compact enough for one truck, were in progress, the two-truck system was taken to the Naval Air Station at Quonset Point, Rhode Island. On December 26, 1942, the first completely blind landing under control of GCL was flown by a Navy SNJ aircraft piloted by Ensign Bruce Griffin, USN. Several hundred successful landings were flown here and the results led the High Command to request a demonstration at the National Airport in Washington in February

1943. The AAF immediately afterwards decided to initiate quantity production of this system. The British Air Commission requested that the trucks be sent to England for demonstration.

6.3.2 Development of Mark II System

EARLY TESTS AND IMPROVEMENTS

Before any Army or Navy contracts had been considered the OSRD had entered into a development contract with Gilfillan Brothers Company for the manufacture of 10 systems which the laboratory felt might be allotted to the Services for experiment and training. Gilfillan engineers came to the laboratory soon after July 1942 when research was in the initial stages and they participated in early tests. In the early fall of 1942 steps were taken toward the development of a second version, called Mark II. The principal improvement was the introduction of the scanning array which was showing good results in the Eagle program. Two prototype arrays, an 8½-ft and a 14-ft, were tested in the early spring of 1943. A newly designed precision indicator was also added. The Mark II system was planned for one truck and a trailer.

Several conferences were held at Camp Evans Signal Laboratory and specifications were drawn up with the help of MIT-RL members. The Army decided to make Gilfillan its prime contractor and the joint U. S. Army-U. S. Navy designation AN/MPN-1 was given because the Navy also ordered equipment from the Bendix Radio Division in Baltimore. At MIT-RL the short title was changed to *ground-control of approach* [GCA] since the military characteristics merely required the placing of an incoming airplane over the runway at an altitude of about thirty feet from which point a visual landing could usually be made.

6.3.3 Field Performance

BRITISH EXPERIENCE

The old Mark I system, accompanied by RL members, was sent to England for trials by the RAF during July and August 1943. On August 23, the GCA landed 21 Lancasters returning from a raid in one hour and thirty-eight minutes. Only 4 failed to make satisfactory approaches and land at the first attempt.

After the final RAF operation, Group Captain Saker, officer in charge of trials, decided to recommend that all contracts for other approach systems be stopped and the American GCA adopted instead.

PRODUCTION AND DISTRIBUTION

The first production unit of Mark II GCA was undergoing preliminary field tests during the month of January 1944. A total of 236 GCA's were delivered before the end of the war: 112 to the Army by Gilfilian Brothers Company, 49 to the Navy by Bendix Radio Division, and 75 to the U. S. Army by Federal Telephone and Radio Corporation; but the sets were slow in getting into combat use.

U. S. Installations. By the end of the war Air Transport Command had GCA sets operating in Iceland; in the Azores; at Gander Field, Newfoundland; Presque Isle, Maine; and others of its bases. Similarly U. S. Naval Air Stations in the United States at Quonset Point, Rhode Island; San Diego, California; Alameda, California; and Whidbey Island, Washington (Seattle), were equipped with GCA and about 20 more installations were planned.

European Installations. In Europe, theater requests did not keep pace with the available supply of sets. Two GCA's were in use in the Mediterranean Theater: one at Fano, the other at Pisa. In the European Theater of Operations General O. P. Weyland was especially anxious, in January 1945, to have each wing and later each group of the Tactical Air Forces and the Air Transport Wings equipped with a GCA. At that time an allotment plan for 12 sets was drawn up but as it turned out only 8 sets were operational by the time of German surrender. Three of these were operated by the Eighth Air Force in England. The first set to go into combat on the Continent was located at A-82 (the night-fighter field) near Verdun, under the Nineteenth TAC.

Early in February 1945, before the regular crew had arrived and before the set was really considered operational, a skeleton crew of two BBRL men and a special installation crew of four Signal Corps men landed, under emergency conditions, a C-47, two P-61's and a flight of P-47's. This equipment was later moved into Germany. Another was the set under control of

the Ninth TAC, at Florennes (field A-78), near Charleroi, Belgium; this was also moved to Germany. The Ninth Bombardment Division of the Ninth Air Force operated a GCA first at Peronne, France, later at Venlo, Holland (field Y-55). A seventh unit, under the Twelfth TAC was used first at Luneville, France, then in Germany. An eighth unit was put in operation at the end of April 1945 near Münster, Germany, with the Twenty-ninth TAC. Over 40 emergency landings were safely carried out by these first few GCA sets to go into operation.

Pacific Theater Installations. There were no GCA's in the China-Burma-India Theater but quite a number were installed or on their way to other locations in the Pacific Ocean area by the time war ended. The Army had sets operating on Iwo Jima, Leyte, Okinawa, Tinian, and Saipan. The Iwo Jima GCA saved several lost or damaged aircraft, including some B-29's returning from raids on Japan. Sixteen or more sets and 16 trained crews were en route to planned installations in the Aleutians, Guam, and elsewhere in the Pacific at the conclusion of hostilities.

6.4 NAVIGATIONAL AND BOMBING RADARS, NAB AND H_2X

6.4.1 Development of NAB and H_2S Systems

From the summer of 1942 to the end of the war the MIT-RL devoted a steadily increasing share of its manpower to the development of radar devices for high-altitude bombing through overcast. In June 1942 work began under J. W. Miller on a device referred to as *navigational aid to bombing* [NAB]. It was a 10-cm system based on ARO techniques, using a lighthouse tube (since it was considered undesirable to fly magnetrons over enemy territory), a PPI, and a cut-paraboloid antenna with a 360° scan. Its use was based upon a recent observation that cities gave stronger echoes than open country. The first NAB system was installed in a B-18 airplane in October and flown unsuccessfully, for it did not give the desired discrimination.

Improvements on Original NAB

In December, when G. E. Valley became project engineer, it was decided to replace the lighthouse tube with a magnetron. NAB was now a modification of the ASV with a newly developed antenna providing what is described as a cosecant squared (csc^2) pattern. Even with this improved system, cities (except those with land-water contrast) were hard to identify, so it was decided in January 1943 to change to 3 cm. This made NAB essentially a 3-cm version of what the British were calling H_2S.

Experiments on H_2S

Work on the necessary 3-cm r-f components was delayed by the low priority acquired by NAB as a result of the conference on radar bombing held at the MIT-RL on February 13, 1943. Dale R. Corson and N. F. Ramsey, both civilian representatives of the AAF, and David T. Griggs, of the Office of the Secretary of War, all gave 15-20-mil bombing accuracy as the Army's requirement for any radar bombing aid. This somewhat visionary accuracy was in no sense claimed for NAB.

However, Valley believed in his system and work continued after 3-cm r-f components were received in April. As a result, H_2X was in existence when Griggs came back from England, where he had been investigating British blind bombing at the request of Robert A. Lovett, Assistant Secretary of War for Air. He brought with him requests from the Eighth Air Force to back this demand for the delivery of twenty 3-cm sets by September 1. The improved resolution of H_2X was a result of its higher frequency and the improved ASD-1 receiver.

Final Design

Production Program. Early in June a program under joint Army-Navy sponsorship was set up. MIT-RL undertook a crash program of 20 sets to be delivered to the Army Air Forces by September 1943. This was under the direction of G. E. Valley and Lt. (j.g.) R. L. Foote, USNR. The laboratory was also to furnish engineering information and advice to Philco, which was to produce the AN/APS-15 for the Navy. Later the laboratory agreed to act as advisor to BTL for the Army's AN/APQ-13.

Model Components. The H_2X and AN/APS-15 consisted of the ASD r-f assembly, the ASG spinner base, the ASG-3 indicator central, and the

ASD-1 receiver, special 3-cm r-f components and an improved csc² antenna, and H_2S ranging circuits. The AN/APQ-13 was identical except for the use of 717-T3 components.

Improvements Following Distribution. By August one H_2X set had been installed in a B-17 aircraft. By September 15 all 20 sets were complete, and the required 12 were installed in B-17's. Philco production began in October. The total Philco production, including modifications (AN/APS-15A and B) was 7,835 sets. The total Western Electric production of AN/APQ-13, begun in December 1943, was 10,995.

Training began at Grenier Field in August under the direction of Griggs. During training it was discovered that r-f breakdowns occurred at high altitudes. MIT-RL men went to Grenier Field and installed the pressurized r-f system that had been originally designed. The later sets were pressurized. In November, a crash training program was set up at Langley Field, using H_2X systems in airplanes, and AN/APS-15 sets on the bench. By October the first of the crash sets had arrived in England, accompanied by two members of the original MIT-RL H_2X group, D. Halliday and S. McGrath.

6.5 EAGLE HIGH-RESOLUTION RADAR, AN/APQ-7

6.5.1 Requirements of High-Altitude Blind-Bombing Device

Work on Eagle, planned as a precision, radar high-altitude blind-bombing device, began in November 1941. The central idea was to produce a set having extremely high resolution using the highest frequency then available. High resolution would be obtained by increasing as much as possible the gain of the antenna, rather than waiting for techniques to be developed at shorter wavelengths.

As a result of a conversation with E. G. Bowen, British liaison representative at the MIT-RL, L. W. Alvarez realized that a practicable radar bombsight need have high directivity in only one plane, and hence required a reflector large in only one dimension. As Alvarez worked it out toward the end of November, the system would operate on 3-cm, and the distinguishing feature of the system would be a linear-array, leaky-pipe (slotted waveguide) diffraction grating 20 ft long, mounted along the leading edge of a bomber wing. Some device would have to be worked out to scan the beam, by changing the electrical properties of the array. It was hoped that the accuracy of such a set would approach that of the Norden sight, then erroneously thought to be capable of 15-mil bombing.

6.5.2 Development of Components

EXPERIMENTS WITH FIXED ANTENNAS

By February 1942, a nonscanning antenna had been built and tests on the antenna pattern were made with very disappointing results, since three distinct lobes were obtained instead of a single beam. In March, the antenna problem was assigned to R. M. Robertson, and various more or less successful methods of eliminating the extra lobes were obtained. By the end of April a leaky pipe antenna had been devised that gave a narrow beam free from large secondary lobes.

In May, Alvarez conceived the idea of the reversed dipole array for use with Eagle and MEW. By reversing alternate dipoles it is possible to reduce the dipole spacing sufficiently to give a single beam. For use with Eagle this could be scanned by varying the cross section of the waveguide. There was a good deal of scepticism about the practicability of such a long array as had originally been proposed; it was felt that a 20-ft array would be quite impossible to align and that phase errors would be enormous. A 13-ft fixed antenna was therefore built and tested; it gave a good pattern with a beam width of less than half a degree.

DEVELOPMENT OF SCANNING ANTENNA

For some time scepticism remained strong within the laboratory, except within the Eagle group itself, so much so that they were forced to work with low priority. In consequence much shop work was done by outside firms. With the promise of a workable antenna the Eagle Project then variously known as radar bombsight [RBS], bombing-through-overcast [BTO], and more picturesquely as every-house-in-Berlin [EHIB] (indicating the accuracy expected) was formalized as a laboratory project with E. A. Luebke as project engineer. He undertook to have a 3-ft scannable antenna constructed, while

in July the indicator group under W. A. Higinbotham began work on an indicator. This was to have accurate ground range sweeps combined with computer circuits, together with an expanded indicator for bombing.

COMPUTER

During the fall of 1942 the idea of a separate computer came into favor; the Norden Mk XV, the General Electric, the Librascope, the Bell Laboratories BTO computer, and finally Bell's *universal bombsight* [UBS], were all considered. Parallel development on circuits for use with all these computers went on for a year. It was recognized that the first goal should be a simple straight-line computer with a stabilized indicator giving an accurate map of the ground.

TEST OF SCANNING ANTENNA

In the summer of 1942 the 3-ft, variable width waveguide scanner was tested; the pattern was poor and losses high, but it radiated and scanned. The 6-ft antenna, tested in November, had improved chokes, but still a limited scan. The idea of alternate end feed, with an r-f switch, was then developed and incorporated in the 8-ft antenna, which also had improved dipoles. After completion of the 8-ft antenna in February 1943, the final production size, a 16-ft antenna was next tried. This was delivered in March, and after a few changes was satisfactorily tested in May.

In October 1942 Robertson thought of mounting the antenna in a wing-shaped fairing or vane under the airplane, instead of in the leading edge of the wing. A plywood vane was designed at MIT-RL and built by the F. J. Hagerty Co. This vane was attached to a B-24 at Wright Field in May 1943 and the plane was then successfully flown to Westover Field for installation of the 16-ft antenna.

During the spring of 1943 work was rushed to permit early flight tests, under the guidance of J. H. Buck, and steps were taken toward production. Early in 1941 the Army had assigned the project number AC-1 to Eagle, an indication of the importance of a precision radar bombing device. In March 1943 the Matériel Command formalized the program, recommending Western Electric, in the interests of standardization, as the contractor. A contract for 5 systems, without computers, was given to Western Electric in May with the designation AN/APQ-7. At this time there was an Army-Bell-Radiation Laboratory conference, the first of many, to define Eagle. The Army wanted a short-range project with a simple straight-line computer but with the UBS Eagle as the ultimate goal. As at many other conferences during the next two years, the relationship of Eagle to the overall bombing program was discussed. Many times it was suggested that Eagle be cancelled in favor of HAB or AN/APQ-10, or later in favor of K-band.

In April 1943 an NDRC contract was given to the Douglas Aircraft Co. for the development of a vane. In May, Eagle became the first project to have the full-time services of a transition office man. J. W. Eggers contributed much to Eagle, especially in coordinating the antenna and vane production. He also became very much interested in an interim, simple Eagle, which would permit the use of the high resolution of the Eagle antenna long before the UBS program became a reality. In June a group of Bell engineers came to work with the various Eagle groups in MIT-RL, a beginning of the close cooperation between the two organizations, and in July, a Douglas engineer came for the same purpose.

RESULTS OF FLIGHT TESTS

On June 16, 1943, Eagle was given its first flight test at Westover Field. The resolution was all that was expected, though there were some troubles with the r-f switch and the flaps which shaped the vertical pattern. However, the electrostatic tube required for the completely stabilized, accurate sweeps in the indicator gave very poor contrast, and the complicated circuits were unstable. It was replaced with a simple sector PPI magnetic tube, which gave a satisfactory presentation of the high resolution afforded by the antenna. This installation was shown to the Army. Although a complete indicator, with stabilized sweeps and an expanded indicator, was working on the roof of Building 24, Luebke, Eggers, and Robertson urged on the Army the advantages of a simple Eagle with magnetic tube.

6.5.2 Design and Specifications of Mark I

In August, Western Electric received an order for 50 AN/APQ-7's, and it was necessary to de-

cide exactly what an AN/APQ-7 set was. Discussions involving the U. S. Army, MIT-RL, and BTL culminated in a conference on October 22, 1943, at which the simplified Eagle Mark I was chosen, in spite of opposition. The Bell engineers did not want to give up the tie-in with their UBS, and certain of the MIT-RL indicator-computer people naturally disliked the shelving of all the effort they had put in. In fact, work continued hopefully on the UBS project for some months. Eagle Mark I consisted of a 16-ft antenna, a 717-T3 modulator and r-f head, a modified 717 receiver, an impact predicting computer, and an indicator with approximate ground range sweeps. BTL accepted an order for 40 preproduction sets, to start in April 1944, with Western Electric production of 612 sets to start in July 1944. MIT-RL agreed to act as the Army's consultant, and close liaison was maintained with Bell until the end of the war.

Eagle became the first radar set designed by RL for which complete specifications were set up before production. The design objective was set at 80 mils bombing accuracy, a figure bettered in production. In November, Douglas agreed to continue work on the B-24 installation, while plans were made for a B-29 installation. When Western Electric, arguing that it was not in the airplane business, asked to have the wings and leading edges supplied by the government, Division 14, at the Army's request, initiated an OSRD contract with Douglas for 50 preproduction wings. The Radiation Laboratory then assisted Bell Laboratories and Western Electric in finding a suitable manufacturer for the antenna. Ex-Cell-O Corp., Detroit, was chosen in December 1943.

Flight Test Results

The MIT-RL B-24 with a Mark I indicator went to Boca Raton, Florida, for the winter where extensive flight tests were made to determine bombing accuracy, and the suitability of the equipment for navigation and for measuring ground speed and drift. Operation was quite satisfactory, and such bombing as was done was well within the specified accuracy.

In March 1944 there was a temporary crisis in Eagle production. Western Electric declared that no sets would be produced that year unless the Army furnished considerable help. At the March meeting of the Stratton Committee, an attempt was made to have Eagle cancelled in favor of K-band, which was claimed to have almost as high resolution, and had a 360° scan. The 60° scan of Eagle had always been severely criticized, and sections of the Army remained opposed though navigation proved to be not especially difficult in practice. However the Eagle Mark I program was kept intact, though Eagle Mark II (with AN/APA-44) and Eagle Mark III (with the UBS) were cancelled. Shortly after this Western Electric determined that it would be possible to meet production schedules.

On May 16, 1944, the first BTL preproduction set was successfully flight-tested. The flight model was sent to the Aircraft Radio Field Laboratory at Boca Raton for tests; acceptance tests were finished by fall. In September the Bell preproduction order was complete, ahead of schedule, and Western Electric, whose order had been increased to 1,660 sets in June, began production.

Modifications and Applications

During 1944 and 1945, MIT-RL worked on various attachments and modifications for Eagle. Camera attachments for taking scope pictures were designed by the laboratory and 25 of them were manufactured by RCC. A supersonic trainer was designed in the laboratory in 1944, and produced by RCC early in 1945. AN/APQ-16, Eagle with GPI, had been under consideration for some time at the end of the war. Plans had been made for mounting the Eagle antenna in the wings of future heavy bombers, B-32 and B-36, with the possibility of an Eagle antenna in each wing to increase the scan angle. Some inconclusive tests were made in the summer of 1944 on the use of Eagle for tank reconnaissance. Eagle was successfully used for blind-approach landings, and there were discussions of the use of Eagle in control of guided missiles (war weary aircraft).

6.5.4 Training and Test Programs

In the late summer of 1944 attempts were made to equip planes of the Eighth Air Force with Eagle. Considerable difficulty was met in this attempt, partly because the U. S. Army, reacting from the H_2X crash program, insisted that the Eagle program be orderly, and partly because the Twentieth Air Force had priority

for its B-29's. Finally one Eagle B-17 was obtained, and arrived in Alconbury in October 1944. Buck went to England to assist in testing and setting up training facilities. The set, when it arrived, was found to have a bad hole in the pattern, which was corrected by careful adjustment of the flaps. An intensive program at RL was initiated to correct this situation. It was found that rigid control of tolerances was required so that Western Electric was persuaded to accept overall supervision of the vane and scanner manufacture and installation. In England flight tests were carried out, and a training program set up for operators and mechanics in the theater.

Boca Raton Training Program

The first Eagle training school, for operators and mechanics, was set up at Boca Raton in December 1944, with assistance from MIT-RL. The laboratory trained the instructors, and also prepared a training movie for the mechanics. When training began in the Second Air Force for the 315th and 316th wings of the Twentieth Air Force, the MIT-RL cooperated extensively. The operators were given basic training at Boca Raton and at Williams Field, advanced training at Victorville, and crew training at Second Air Force bases. The MIT-RL men worked to improve crew training. In addition one man from the laboratory was stationed at the headquarters of the 316th wing and one at each of the four groups in the wing. MIT-RL also trained the personnel in the Bowditch Project of photo reconnaissance. This was the first time an extensive program of scope photography of intended targets was undertaken before actual operations began.

Tests at Orlando

Almost the only program in which the laboratory did not assist was the AAF Board tests at Orlando in the beginning of 1945. The men conducting this program were H_2X operators who knew little of Eagle and disliked the limited scan. They solicited no help or advice from either the laboratory or BTL. After somewhat limited tests, using poorly conceived bombing procedures, they turned in a most unfavorable report, though they admitted that Eagle had a higher bombing accuracy than other bombing radars. This adverse report may have delayed the operational use of Eagle, but did not prevent its eventual use.

Field Application

Although just too late to become operational in Europe, Eagle was used in several successful B-29 strikes by the 315th wing in the Pacific. The bombing of the Maruzen oil refinery on July 6-7, with 95 per cent destruction, was the most spectacular of these operations. General LeMay, in a telegram of commendation said "This performance is the most successful radar bombing of this command to date."

6.6 BLIND BOMBING AT SEA, AN/APQ-5

6.6.1 Initiation of LAB Project

A most significant by-product of the laboratory's first participation in the antisubmarine campaign was the development of equipment permitting low-altitude blind bombing of ship targets. One of the men of Colonel Dolan's First Sea Search Attack Group proposed to MIT-RL staff members who were stationed at Langley Field to keep the equipment in running order, that a device permitting the bombing approach to be done "blind" would be of inestimable value. The development was undertaken, and in a month or two an experimental attachment, in the form of a simple computer with its own indicator that tied in to the optical bombsight, was ready for test. The experimental drops, made at Langley Field in October 1942 and later at Eglin Field, Florida, were so successful that it was resolved to give this equipment serious consideration. A development contract for this device, usually referred to as *low-altitude bombing* [LAB] or as AN/APQ-5, was given to the BTL. The Bell engineers were shown the MIT-RL equipment and in their own development followed the fundamental approach without deviation but substituted their own computer circuits and designed the device for use with the Western Electric SCR-717 equipment. Proof tests were run on the AN/APQ-5 in April 1943 with RL and BTL personnel cooperating.

6.6.2 Performance in Pacific Theatre

The first of these radar sets saw combat, on what was distinctly more than an experimental

basis, against Japanese shipping in the South Pacific in 1943 and 1944. The first squadron of Liberator bombers equipped with the SCR-717 and the APQ-5 reached its Pacific base in August 1943. It had been organized and trained at Langley Field by Col. Stuart P. Wright, A.C., who had been attached to MIT-RL as Air Forces liaison officer during the period of LAB development. With this equipment the Army Air Forces were able to enforce an interdiction campaign that together with the attacks of submarines, virtually severed Japanese communication lines to their South Pacific outposts.

Since an uninterrupted supply system is essential in island warfare, one of the primary tasks of the U. S. forces in the Pacific was strategically to blockade Japanese merchant shipping lines. When convoys were reported, large-scale daylight attacks could be made, the operations being well worth the number of planes required. However, over half the Japanese shipping sunk in the Pacific had been operating, not as convoys, but as single ships which entered patrolled waters after dark. Since a patrol can carry only a limited number of bombs due to the vast distances it must travel, it must be able, upon sighting an enemy ship, to score on the first, or at most, the second run. This is a difficult and complicated assignment, especially at night, since the target is small, the bomb load limited, and evasive action sure to be taken.

Old antishipping technique, in which bombers flying in daytime sweeps bombed from medium and high altitudes, required a prohibitive number of planes. But single "snoopers," equipped with SCR-717 and LAB, and patrolling by night the known Japanese shipping lanes, could surprise the radarless, poorly defended merchantmen and barges, and, coming in under conditions of zero visibility at altitudes of approximately 1,000 ft strike before evasive action could be taken or defenses manned.

Three such squadrons of snoopers are known to have operated in the Pacific, one with the Fifth Air Force, one with the Thirteenth, and one with the Fourteenth. The Thirteenth Air Force was the first to receive a squadron with LAB and to introduce the new equipment into combat. In late August 1943 after a two months' period of intensive training at Langley Field, Colonel Wright, with a selected group of pilots, navigators, bombardiers, and technicians, and ten LAB B-24's arrived at Thirteenth Air Force Headquarters at Espiritu Santo in the New Hebrides and then moved on to Guadalcanal. Colonel Wright remained with his group approximately one month. During this early operational period of 67 combat missions flown, 46 bombing runs based on radar contacts were made with 17 direct hits. The Wright Project was transferred to the 868th Bombardment Squadron which was for a short time based at the Munda Air Base in New Georgia, and which continued its antishipping depredations until fairly late in the war when, because of the scarcity of enemy shipping, it became a general purpose bombing force.

Colonel Wright might also be considered responsible for the second LAB squadron that left for the South Pacific. In October 1943, Lt. Col. Edward W. Scott, who had earlier been convinced by Colonel Wright of the potentialities of the LAB project, took 12 B-24's with their specially trained crews out to the Fifth Air Force. There, as the Sixty-third Sea Hawk Squadron of the Forty-third Bombardment Group they operated in the Rabaul-New Hanover area, extending their territory north and west to Mindanao later in the same year. During a cross-sectional period of four months, this squadron made an impressive record, accounting for 32 per cent of all ships sunk by the Bomber Command. In so doing, the squadron used one-fourth the number of planes, bombs and personnel, the rest of the Command employed in its entire antishipping activity. For attacks against shipping, the effectiveness of the LAB squadron was approximately 400 per cent greater than that of the rest of the Command's aircraft not so equipped. By spring of 1944 the targets available to the Sixty-third Sea Hawk Squadron had become limited, for the enemy was using only smaller vessels with shallow draft and was operating them close to shore.

Admirable as were the records of the Fifth and Thirteenth Air Forces in their nighttime interdiction work, that of the Fourteenth was still more impressive. The Fourteenth's LAB-equipped 308th Group (H) operating under Lt. Col. William D. Hopson during the summer of

1944 in the China Sea had the advantage of by far the largest amount of Japanese shipping. It was estimated that from 750,000 to 1,000,000 tons of Japanese shipping passed within range of the 308th's bombers each month and the group was able to average the extraordinary figure of three sightings and 1,200 tons sunk per sortie. Unfortunately the number of planes available to the group was inadequate to deal with the traffic density and two out of three targets picked up in the China Sea went untouched. In spite of the shortage of planes, however, during the first three months of Hopson's Project, 113,400 tons of cargo vessels and 7 warships were sunk and another 54,300 tons damaged, while during the month of September, a record score of 110,000 tons or 1,700 tons per sortie was chalked up.

6.7 AIRBORNE GUNLAYING SYSTEMS, AGL-1 AND AGL-2

6.7.1 Initiation of AGL Project

The development of gunlaying systems [AGL] were first seriously considered at MIT-RL as a result of a request from General Arnold to E. L. Bowles, at that time secretary of the Microwave Section of NDRC. As a result of this request Bowles accompanied by L. N. Ridenour attended a conference at the Douglas Aircraft Company at El Segundo, California, early in July 1941. The Air Corps as well as the Douglas Company was anxious to have radar equipment installed in the new attack bomber, the XA-26A. The mockup of the aircraft was based on the use of the AI-10, but Douglas representatives, particularly F. R. Collbohm, wanted a more elaborate fire-control radar, since the plane was to carry a computer which would make firing of the guns accurate beyond point-blank range. It was decided that Douglas should plan on an AI-10 installation, but GE was given a contract to modify this equipment for gunlaying, and in August the AGL-1 project was officially started at MIT-RL.

6.7.2 Characteristics of AGL Systems

AGL-1 Model

AGL-1 was a 10-cm system derived from the AI-10, which permitted search, automatic tracking, and blind firing against enemy planes at night. After the operator selected the target, the system locked on it, and thereafter automatically supplied azimuth, range, and elevation data to the computer which directed the movable turrets. It was designed primarily for the XA-26A, and secondarily for the P-61. Various forms of antenna were developed, and there was some work on an AGL-1 Mark II, a lighter weight version. By January 1942 the system was operating on the ground, and was soon after flown in a B-18. Flight tests were successful enough to persuade the Signal Corps to order 200 sets from GE of a production version called the SCR-702A (later AN/APG-2). This was followed in January 1943 by an order for 200 sets of the SCR-702B (AN/APG-1) from Western Electric.

AGL-2 Model

By January 1942 plans were being made for several other types of airborne gunlaying equipment in all of which MIT-RL took some part. AGL was, however, always a small project, with rather low laboratory priority. The AGL-2 (SCR-580) was a 3-cm system being undertaken by the Sperry Gyroscope Company, intended for use in the XB-29. MIT-RL started work on this in May 1942, and tested a system made up of parts supplied by Sperry. The first Sperry system was given flight tests at Eglin Field early in 1943, and the contract was terminated in May 1943, when other systems appeared more promising. The AGL-3, a 3-cm system for installation in a U. S. Navy PB2Y-3 was almost entirely a Sperry development, though MIT-RL gave some advice. The AGL-4 was a 3-cm system to provide very accurate ranging for the 75-mm cannon in the XA-26B. This modified form of the AI-3 was flown in an AT-11 plane at MIT-RL in March 1943, but the project was cancelled soon after. The AGL-5, for the XP-71, never was developed for want of a plane.

AGL-3 Model

Despite all this *va-et-vient*, the only AGL systems produced in quantity were the AN/APG-1, at Western Electric, and the AN/APG-3, a relatively lightweight set for B-29's, at General Electric. GE's contract for the AN/APG-2 was cancelled in October 1944, partly to prevent interference with the AN/APG-13 (Falcon), and partly because the AN/APG-3 was promising.

Work on the AN/APG-3 began at the end of 1943, and the system was given ground tests in the summer of 1944. Sperry was given a contract for a similar system, the AN/APG-16, and production on both these systems was pushed in 1945. These systems represented an attempt to produce a more practicable AGL than the heavy (400-500 lb) systems previously developed, and was part of the intensive program to provide every conceivable form of radar for the B-29.

6.7.3 Field Application of AGL

The AGL program suffered undoubtedly from the fact that, having been conceived very early, the systems that emerged were modifications of a fairly primitive form of microwave radar. The sets were heavy in consequence, and therefore were unpopular with the Army forces. There was never much enthusiasm within MIT-RL, even in Division 9, which at one time tried to have them transferred to Division 8.

It must be kept in mind, however, that tactical considerations, changing with the course of the war, had an enormous influence on the amount of emphasis placed upon this as well as other airborne programs. When AGL was first conceived it was expected that bombers might fly solitary missions or in loose formation, often at night, and that protection against enemy fighters, especially nightfighters, would be urgently needed. As far as heavy bombardment aircraft were concerned this was never the case. The doctrine of daytime, tight-formation flying which had been adopted reduced the importance of the AGL type of equipment. Although, until the last stages of the offensive against Germany and against Japan, fighter opposition was often serious, it never threatened to cripple the air offensive, which would have meant greater concern for bomber defenses.

6.8 AIRBORNE RANGE-ONLY [ARO] AND AIRBORNE GUNSIGHT [AGS] RADARS USING LIGHTHOUSE TUBES

6.8.1 Initiation of ARO Project

The *lighthouse tube transmitter-receiver* [LHTR] systems, designated variously as ARO, AGS, Falcon, TW, and their modifications, all were designed around the same standard unit. This is a lightweight, pressure-tight unit containing a transmitter-receiver, with lighthouse tubes, and a power supply. The LHTR Mark I was developed by H. L. Schultz in 1942 in the course of his work on ARO. A lighter, smaller unit, the LHTR Mark II, was developed in 1943 for use with another system, but was never put into production. The first LHTR operated at 10.7 cm; in 1943 the band 11.0 to 12.5 cm was officially assigned for LHTR operation. The LHTR unit is used in all its applications without internal modification, though various improvements have been incorporated since 1942.

Airborne range-only [ARO] was formulated as a project in April 1942 following a request from the Bureau of Ordnance. The U. S. Navy had been interested since January 1942 in a system to be combined with the Ford Instrument Company's fire-control system, but the idea was not then practicable. The U. S. Army became interested in June 1942 and most of the subsequent development was done for the AAF.

Development of ARO Equipment

Requirements. Range for the fire-control mechanisms then in use was supplied by rather crude stadiametric measurement. ARO was to supply range automatically, with no attention from the gunner. The necessary components were developed in the spring and summer of 1942. These were an LHTR and a range unit, both light and compact, to be used with an 8-in. paraboloid. RCC agreed to build 10 LHTR's and 6 range units, and the Philco Radio Corporation and the Galvin Manufacturing Company received small educational orders. Production was delayed by the great difficulty experienced in obtaining lighthouse tubes.

Testing. During the fall of 1942 the laboratory-built ARO was given flight tests in a B-18. In January the system, in which a polystyrene rod antenna (end-fire array) was substituted for the paraboloid, was sent to Wright Field for tests in a B-17. After successful firing tests with improved units at Eglin Field, Florida, the U. S. Army ordered 400 sets (designated AN/APG-5) from Galvin. Meanwhile the Navy was conducting exhaustive tests at Norfolk, Virginia. The Army laid out a series of future tests including the installation of ARO in a B-25G for use with 75-mm cannon (this was the start of Falcon)

and firing tests of ARO in the Emerson lower ball turret of a B-17; possible installation in B-29's was also considered.

Production and Application. RCC production began in June 1943. Galvin produced their first 6 (preproduction) systems in April 1944. Since there was little chance of quantity production in 1944, the U. S. Army agreed to cancel all orders except for the 25 preproduction systems, and the U. S. Navy requirement was reduced to 80 sets. A large part of the delay was caused by engineering difficulties arising from the automatic features of the system. There were also conflicts with other, more urgently needed, LHTR systems. After various modifications to permit the use of ARO with the K-15A gunsight, Galvin resumed production in May 1945.

In January 1944 plans were made to install ARO in B-29's. One installation (called AN/APG-14) was made in August 1944 as part of Project Wasp. A more important ARO project was Figaro. This was the installation of ARO in B-17's, and, later, B-24's, first discussed in the spring of 1944. Five B-17's arrived at Bedford in October of that year; by December they were on their way to the Fifteenth Air Force in Italy, followed by 5 B-24's in May 1945. These installations were successfully flown on many missions, but no tactical experience was gained for no enemy opposition was encountered.

6.8.2 Initiation of AGS Project

AGS MARK I MODEL

Work on an *airborne gunsight* [AGS] was begun November 1, 1942, with J. V. Holdam as project engineer. Somewhat earlier the laboratory had received requests from the Army for such a project. It was decided to develop first, a lightweight system based on ARO, without a computer, for installation in the Emerson tail turrets of B-24's, and second, as a long-range project, a system for use with lead computing sights. The necessary modifications included the addition of conical scan, the precise coordination of the radar axis of scan with either the boresight line or the sight line, and the addition of an indicator unit. The indicator presentation was a spot the position of which was an indication of target bearing, and on which grew wings whose size varied inversely with the range. Since there was some doubt of the adaptability of the LHTR to such a system, an alternate development of a low-voltage magnetron transmitter-receiver, the SMTR, was initiated. This, known as the AN/APG-10, was cancelled in November 1943.

By April 1943 a complete system, with an end-fire array antenna, was undergoing flight tests in an AT-11. In July an AGS Mark I was flight tested in the Emerson tail turret of a B-24. An NDRC contract for 25 AGS Mark I systems was given to Galvin to provide models for experiment and possible operational trial.

AGS MARK II MODEL

Development continued on various AGS systems and by October 1943 there were several recognized versions. The AGS Mark I (AN/APG-8) had no computer and was designed for installation in an Emerson tail turret. The AGS Mark II (AN/APG-8B or AN/APG-15) was the AN/APG-8 modified for installation in the tail of a B-29. The AGS-2 Mark II was the low-voltage magnetron version of the AN/APG-15, and the AGS-3 Mark I was an LHTR system for installation in an Emerson tail turret in conjunction with the Fairchild lead computing sight. The Army, encouraged by preliminary tests, set up a requirement of 3,500 sets in 1944, with contracts let to the General Electric Company and to Galvin Manufacturing Company. In May 1944, however, Falcon was given precedence over other LHTR systems, and AGS contracts were curtailed.

DEVELOPMENT OF AN/APG-15

At MIT-RL intensive work was being done on the problem of boresighting in an effort to develop satisfactory techniques for factory and field. In August 1944 the Army requested assistance from the laboratory for Project Wasp, a crash program to install AN/APG-15 in seven B-29's and AN/APG-14 in one B-29. Work was begun in November and completed on schedule in the same month. The result of this program was the development of the AN/APG-15B. This provides automatic radar range to the computer for visual tracking, while at night it gives tail warning and point-blank bearing information. Five of these B-29's were sent to the 58th wing, Twentieth Air Force, in India for combat test-

ing. The systems operated successfully, but little tactical information was obtained.

By February 1, 1945, GE had produced 272 AN/APG-15A's; thereafter only AN/APG-15B's were accepted. The total production was 9,376. Both the 315th and 316th wings of the Twentieth Air Force were equipped with AN/APG-15. Operation was fairly satisfactory, but little tactical information was ever obtained since there was little enemy fighter opposition.

6.9 FALCON (AN/APG-13A), VULTURE (AN/APG-13B), AND PTERODACTYL (AN/APG-21)

6.9.1 Development of Falcon

Requirements

After successful tests of ARO in the spring of 1943 it was decided to test the system in a B-25G with 75-mm cannon. Such an aircraft has a fixed gunsight mounted parallel to the cannon boresight axis; the pilot aims the cannon by flying the plane so that the sight is lined up with the target. Accurate range determination is necessary.

Adaptation of ARO to Falcon

ARO in a B-25G was tested in September, and MIT-RL began to modify the basic ARO components. This involved elimination of the automatic range unit, range servo, and calibrator, which were replaced by an M-scope, and the addition of a ballistic cam to make the rotation of the range adjusting shaft linear with range. The radar operator adjusts a hand crank to keep an electronic marker in coincidence with the target signal; this provides range adjustment of the gunsight through a flexible shaft. In December 1943, a laboratory system was ready for tests at Eglin Field and RCC had under way the production of 30 systems for a special experimental squadron. In April 1944 the first RCC order was complete, and the Army asked for 120 more systems. At the same time an order was given for 880 sets to be built on a crash basis, the M-scopes at the General Electric Co. and the LHTR units and antennas at Galvin Manufacturing Company.

By June 1944 the first experimental squadron was in action with the Fifth Bomber Command in New Guinea. The equipment performed well, though ship targets were already scarce. By fall the Fourteenth Air Force was using Falcon with great success. Operational experience showed the necessity of a device to permit setting in actual airspeed, since in combat varying speeds were used. The laboratory provided such an attachment.

Development of Falcon

During the summer of 1944 the Army asked for a unit to permit mechanical instead of hand tracking, and it became obvious that a modification of Falcon for use over land was required. This was the start of Overland Falcon or Vulture. The Vulture presentation, in which all targets in the radar beam appear on the indicator, but with the target signal clearly differentiated, was proposed by E. H. B. Bartelink in May 1944. Falcon can be readily converted to Vulture by the addition of a subpanel to the M-scope, the replacement of the antenna by an AGS scanner, and the addition of an aided tracking unit to replace the hand crank which feeds range information to the gunsight.

The laboratory built model was successfully flown in November 1944. In February 1945 General Chennault requested 30 modification kits to convert Falcon to Vulture; his Fourteenth Air Force had used Falcon with great success but they had been pushed back in China and needed an overland system. RCC undertook a crash program which was completed in August. During the spring and summer of 1945 a good deal of thought was given to the problem of adapting Falcon or Vulture for rocket firing. The Applied Mathematics Group at Columbia gave a good deal of help on the problem of designing the necessary computer and ballistic cams.

Development of Pterodactyl

By the beginning of November 1944 Automatic Vulture or Pterodactyl was ready for flight tests. This was an automatic system which searched in range, and only locked on a target when both range and directional information was correct. In June 1945 work began at the laboratory on assembling 5 systems from the improved ARO components then in production. RCC had an order for 12 units which were completed in October 1945.

6.10 LOW-VOLTAGE MAGNETRON SYSTEMS, AN/APS-10

6.10.1 Experimental Work

The low-voltage magnetron systems are closely allied with the lighthouse-tube systems. Both types of transmitters draw only a small amount of power and hence are more suitable for the design of lightweight radar sets where range is not the principal consideration. Development of experimental low-voltage magnetron systems had proceeded far enough by the beginning of 1943 so they could be conceived of as possible alternates for the LHTR systems. Work was also done on a low-voltage magnetron tail-warning system, the ASJ. The only low-voltage magnetron system that was pushed beyond the initial stages of development was the AN/APS-10, also known as *blind-flying radar* [BFR]. This was derived from the LWASV, a lightweight LHTR system begun in November 1942 and terminated in June 1943, since it did not meet the U. S. Army requirements for weight and performance.

6.10.2 Development of AN/APS-10

Experimental Objectives

At the time the LWASV project was terminated the U. S. Army expressed an interest in a very lightweight ASV, to be called the AN/APS-10, which would be simple and reliable, with relatively short range, suitable for use with beacons and IFF. During the summer of 1943 work was started by H. L. Schultz on the XMTR, a 3-cm, low-voltage magnetron transmitter-receiver. As development proceeded it appeared that the system based on XMTR would be even more useful as a navigational device than as an ASV system. The need for such a navigational aid was strongly urged upon the laboratory by Colonel Stuart P. Wright on his return from the Wright project mission to the South Pacific.

Design Characteristics

By the beginning of 1944 the first laboratory model was flying successfully. This had an 18-in. csc^2 antenna, the XMTR unit, but only a makeshift indicator. Various improvements were made and at an Army-Navy meeting on February 25, 1944, the Army decided that the AN/APS-10, based on the XMTR, would definitely meet its requirements for a lightweight, simple navigational device for use on transport planes. Several engineers from GE, the chosen manufacturer, had already arrived at the laboratory to work with the system, and on March 22 there was a meeting at which the AN/APS-10 program was set up. The laboratory agreed to act as consultant, with A. Longacre as project engineer for production, while R. L. Sinsheimer remained project engineer for the work at the laboratory. In the succeeding months details of the system were thoroughly worked out. It was designed above all to be reliable, rugged, simple to operate, and easy to service. The number of controls were sharply limited, so that reliable automatic tuning was imperative; for easy servicing the various units were designed to be replaceable and completely interchangeable.

Production and Field Application

The GE engineers remained at MIT-RL until the summer of 1944. By the time they left the engineering drawings were complete. The laboratory built three prototype systems based on these drawings, one of which served as the GE prototype, while the others were used for tests. A new and improved scanner was designed and manufactured by the Houston Corporation at the instigation of RL. Two hundred of these were purchased by the Army through GE as extra equipment. At the beginning of 1945 the system was demonstrated to Troop Carrier Command [TCC], which was very enthusiastic. A 30-in. scanner was developed for TCC, to give improved resolution for navigation.

Production at GE was slow, due largely to procurement difficulties and necessary design changes. The 50 preproduction systems were completed by April 1, 1945. Since GE had subcontracted the manufacture of components, though still assembling and testing the sets, quantity production was delayed until June. By August, 300 sets a month were being produced. Such sets as were available before the end of the war were installed in C-46 transport planes for the TCC. It is reported that C-46's with the APS-10 were in Japan in September 1945.

Chapter 7

SHIP SYSTEMS

7.1 SHIP CONTROL OF INTERCEPTION[a]

7.1.1 Development Program

As pointed out in Section 2.2, the earliest production shipboard system available to the U. S. Navy was the CXAM, an aircraft warning system operating at 200 mc per sec, the first unit of which was delivered in May of 1940. This set suffered from the defects characteristic of low frequency, and its usefulness was impaired by its lack of height-finding features.

Requirements

The control of the interception of enemy planes from an aircraft carrier requires accurate information on the altitude as well as azimuth and range of the approaching craft. The cooperation of Division 14 in the Navy program for the development of such radar dates from December 8, 1941, when the Navy, in Project NS-101, proposed the development and construction by NDRC of a model radar that would be capable of the accurate determination of the altitude of approaching bombers. As a result the completed experimental set designated CXBL was installed in the carrier *Lexington* in March 1943 as stated in Section 5.1. This was the first height-finding set on an American aircraft carrier.

SM and SP Systems

The first SM production model of the CXBL was installed on the carrier *Bunker Hill* in September 1943. The SP, a lightweight version of the SM, was to go into production nine months later than the SM. These sets required that the radar-controller point the antenna at only one plane at a time in order to determine its height, a factor that seriously limited the traffic handling capacity of the system and simultaneously prevented this powerful microwave system from being used for low coverage.

SCI or CXHR System

Requirements. On August 18, 1943 the radar design section of the Bureau of Ships [BuShips] requested MIT-RL to develop a radar that would give the height of all aircraft within 50 miles every 15 seconds and at the same time provide high- and low-microwave coverage. The desired coverage was to be 80 miles on all aircraft below 40,000 feet and below an elevation angle of 20°. Since the antenna weight was an important design limitation it was planned to place the antennas for both the height-finder and the search system on the same stabilized mount.

Operational Characteristics. A Robinson scanner was selected as the feed for the height-finder. At 8.5 cm the Beavertail beam of the height-finder was 3.5° wide and 1.1° high. This beam scans from the horizon to an elevation of 11°, 600 times per minute. At the same time the mount rotates in azimuth and height data is continuously presented on RHI's at the several consoles. As the mount rotates at 4 rpm the height beam hits the target 3¾ sec later than does the search beam. The search beam is 1.7° wide in the horizontal direction and is fanned up to 18° vertically.

All the information presented by these two radar systems on the same mount is presented at any one of the five mutually independent consoles. Each console has a PPI, an off-centered PPI, and an RHI. The width of the azimuth sector where signals may appear on the RHI is adjustable. The coordination of the three scopes on each console, the use of five independent consoles for each equipment, and the ability of this system to provide height data under conditions of continuous scan are reasons for its greatly superior traffic handling capacity, when compared to SM or SP.

Design Problems. The most difficult problem connected with this type of system was that of designing the Robinson feed. An experimental system involving only the height-finder was put into operation early in March 1944 on the roof of Building 6 at MIT. This system had a range of 45 nautical miles on a two-motored plane (SNB). Its height accuracy was satisfactory

[a] This section was prepared by J. S. Hall, project engineer SCI.

and its coverage to 11° elevation angle was adequate. In April 1944 it was decided that the two prototype sets (later designated CXHR by the Navy) should be built. The General Electric Company [GE] agreed to build most of the components for these two sets and to deliver them by January 1, 1945. The MIT-RL was to design and build the two main control panels and the two r-f heads. These r-f heads were to be placed between the reflectors on the mount.

EXPERIMENTAL INSTALLATION

A building with a radome on top of it was constructed at the Spraycliff Field Station located at Beavertail Point, Jamestown, Rhode Island, which would house both the equipment and the mount. During April, May, and June the height-finder was moved from the roof of Building 6, and, together with an early warning dish, was placed on a United Shoe Machinery mount. This mount was installed in the radome at Spraycliff. The experimental set-up was designated SCI and was heavily depended upon as the radar used to direct flyers in night interceptions in the night-fighter training program at Beavertail. Many such flyers later saw action in the Pacific.

FLIGHT TEST RESULTS

Beginning in January of 1945 W. O. Gordy had taken over the responsibility of carrying out experimental flight tests with the experimental search system at Fisher's Island. Flight tests were run throughout this year and work was conducted in close cooperation with the antenna group at Ipswich. The early experiments showed a considerable amount of reflection from the water and the resulting peaks and nulls gave spotty coverage. This was ascribed to the fact that the energy was horizontally polarized. A vertically polarized antenna with a 5-ft by 14-ft dish and a three-horn feed was then constructed. Gordy obtained results which, while not quite as good as requested by the Navy, seemed adequate. He found that a two-motored plane could be followed consistently to 80 nautical miles up to altitudes of 20,000 ft and in to elevation angles of 15 to 18 degrees. He then returned to the laboratory in December 1944 and issued a report, RL-703, describing this work. The complete SCI system was demonstrated to the Navy in July 1944 at Spraycliff.

DIRECTOR CONSOLE DESIGN

During May, G. W. Fyler of GE, who was originally scheduled to produce the SCI consoles, conceived the idea of building a "soda fountain" console around which all fighter-director officers would sit and obtain their data from a single skiatron. In the meantime MIT-RL had built two experimental consoles. The Navy was anxious to see both types tried out and consequently NDRC authorized Fyler to build the type which he had suggested and to place it in competition with MIT-RL consoles at Spraycliff on July 1. The Navy decided in July that the type developed by MIT-RL where each fighter-director officer was at a different console separated from the others was the better solution. Fyler then agreed to build eight consoles according to MIT-RL specifications.

7.1.2 Production and Training Program (CHXR and SX Systems)

In the fall of 1944 the Navy ordered four production systems designated SX from GE. Delivery was to start in July 1945. Early in September a number of GE engineers came to MIT-RL and worked during September, October, November. December, and part of January designing parts of the SX system. During this same time and the early months of 1945 the laboratory built the two main control panels and r-f heads.

Eighteen officers and men spent about eight weeks at MIT-RL during May and June 1945 in an intensive training program. The RL training group under H. H. Wheaton had charge of this training program.

The first CHXR system was tried on the roof of MIT Building 20 in May 1945. Subsequent flight tests showed that the height system had a range approximately ten miles greater than that which had been obtained a year previously on the roof of Building 6. This improvement was the direct result of an improved Robinson feed. The early-warning system had the same coverage and was about equally solid as that which Gordy reported in RL-703.

BuShips ordered 41 SX systems from GE on February 24, 1945, with delivery of these systems to start in March 1946.

In June the second CHXR system was installed at a U. S. Naval Air Station on St. Simon

Island, Georgia. The system on the roof of Building 20 was shipped and installed on the carrier *Midway* in July 1945. The first production SX was installed on the carrier *Franklin D. Roosevelt* in August 1945. The performance of each of these systems was similar to that found on the roof of Building 20 as regards the height-finder. However, the early-warning of system seemed to have gaps in its coverage of 8° or 9° elevation angles. These gaps were serious and still need to be thoroughly investigated. The range, however, on the search part of these three systems was found to be somewhat greater than had been anticipated. This fact suggests that some of the energy which was to be radiated at 8° or 9° is going into the main horn. Since similar problems have been solved in other radars, this difficulty can undoubtedly be remedied.

7.2 GUN FIRE-CONTROL SYSTEM MARK 56

7.2.1 Origin of Mark 56

The gun fire-control system Mark 56, of which the radar Mark 35 is an integral part, is an outgrowth of the automatic tracking developed in XT-1 and the SCR-584. It is an attempt to arrive at a balanced integration of radar and computer into a director system functioning as a unit and represents a break with the policy of trying to adapt radar sets to gun directors designed before the advent of radar or planned without radar as the primary source of data. The Mark 56 is an intermediate-range director to control Navy .38-cal, 5-in. AA guns.

The Bureau of Ordnance [BuOrd] request for the Mark 56 grew out of conversations between I. A. Getting and H. L. Hazen with Captain Murphy in the summer of 1942. Captain Murphy was pleased with Getting's suggestion that MIT-RL would like to undertake an integrated job for the Navy. Further conversations with Lieutenant Commander Irven Travis, in charge of the AA Direction Sub-Section (Re4c), brought out the information that BuOrd would like NDRC to carry the project through to prototype design. The project was requested and endorsed by the Navy's coordinator of research and development on May 19, 1943, and was assigned jointly to Divisions 14 and 7 of NDRC, although Division 14 was given administrative responsibility for contract work.

The project was coordinated at MIT-RL by I. A. Getting, and H. A. Kirkpatrick was appointed project engineer, assisted by R. P. Scott, for gun director Mark 56, and H. S. Sommers for the radar Mark 35.

7.2.2 Mark 56 Systems

Function and Operation

Functionally the gun fire-control system Mark 56 is divided into three systems: (1) radar Mark 35 which has the functions of locating and tracking the target and of supplying position and rate data to the computer, (2) the director proper, whose function is to furnish present position data to the computer plus target angular rates in a stabilized system, and (3) the computer which supplies accurate gun orders and fuze time.

The Mark 35, operating on 3 cm, is the first radar to combine fixed polarization with conical scanning and automatic tracking. Fixed polarization gives freedom from Window and other kinds of jamming. Spiral scan (wide beam) is used for target acquisition. When the target is picked up, the operator switches to automatic tracking and conical scan (narrow beam). A nutating antenna keeps the plane of polarization always vertical. The range system, with its very narrow gate, permits tracking of an aircraft when it is separated from another by as little as 25 yd in range (the improved range gate on SCR-584 was 60 yd long).

The director makes use of a precessing line-of-sight gyro and computer, designed by MIT-RL, which together with a vertical gyro and stable vertical (adapted from a vertical designed by GE) keep the system on an even keel so that tracking information is always given in stable coordinates.

Production and Application

Getting and others from MIT-RL attended a meeting at GE, on December 30, 1943, to discuss details of the OSRD contract which GE had agreed to accept for the development of components and the eventual construction of two prototype models of the Mark 56 system. From this time on there was an exchange of informa-

tion between GE and RL and a division of responsibilities for the development of the model, Mark 56X, set up by the laboratory at its Heathfield Station at Fort Heath, and also an experimental model at Schenectady. The laboratory built two other experimental models, Mark 56A and Mark 56B.

The first radar signals on Mark 56X were obtained on December 28, 1944. From this time until the end of the war tests were run at Heathfield. The complete system Mark 56 Model A was set up at Heathfield while Model B, without the ballistic computer, was installed aboard the destroyer USS *Winslow* in December 1945. In the fall of 1945, the U. S. Navy placed a production order with GE.

Chapter 8

PROJECT CADILLAC, AIRBORNE EARLY-WARNING RADAR SYSTEMS

8.1 INTRODUCTION

THE PROJECT which absorbed the largest portion of MIT-RL's attention and effort in the last year of the war was the development of a highly complex mass of equipment first referred to as *airborne early warning* [AEW] and later for security reasons called "Projectile Cadillac," after Maine's Mount Cadillac on the peak of which an experimental version of the equipment was tested for several months. Cadillac was America's most urgent radar project in the several months before the end of the war; it can fairly be described, also, as the most complex electronic undertaking of the war from an administrative as well as a technical standpoint. The organization and conduct of this program, involving the close cooperation of many separate groups, with MIT-RL serving as the principal coordinating agency, is a wartime research and development story well worth careful study.

8.1.1 Purpose of Project Cadillac

The purpose of Project Cadillac was to overcome the chief weakness of shipboard search radar, namely, its inability to see beyond the horizon. The Japanese fully exploited this horizon limitation, coming in on our ships as low over the water as possible. In 1944 this technique was used in their effective Kamikaze attacks; a variety of tactics was used in making the attacks, but in particular the Japanese found they could circumvent the radar defenses of the fleet by making their final attacks from the zenith where there was no radar coverage, or close to the surface below the beams of the long wave search radar of the ships. The best defense for all tactics was to pick up the planes at as great a distance as possible as they approached the task force. The Kamikaze attack made the extension of the fleet's radar warning range a top priority Navy problem just when the emphasis in the American war effort shifted from Europe to the Pacific.

The Cadillac equipment could also serve an important role (increasingly so as our forces in the Pacific grew in numbers and complexity) in coordinating task force and amphibious operations. For example, in such an operation as the invasion of Japan, when vast armadas of ships and planes would have to be used, the airborne relay radar system could provide all CIC simultaneously with comprehensive data on the disposition of both friendly and enemy ships or aircraft over a wide area.

8.1.2 Origin of Project Cadillac

The airborne-relay radar, which was the key device for realizing the Project Cadillac idea, grew out of an earlier MIT-RL development. In June 1942 the Committee on Joint New Weapons and Equipment had suggested developing a relay link to extend the range of a radar set. Soon after the Navy requested the laboratory to investigate the possibilities of such equipment and to develop a unit for a Service test. A television transmitter-receiver, loaned to the laboratory for two weeks by RCA, was set up in Building 24. On August 14, 1942, transmission on a radio link between Building 24 and an experimental radar system on the roof of Building 6 was successfully demonstrated.

8.1.3 Development of AN/APS-14

Difficulties encountered in these tests led to the decision to substitute frequency modulation for amplitude modulation. In September an experimental FM television transmitter was loaned by Zenith Radio Corporation, and in the following months successful FM transmission between the two buildings on the campus was obtained. Plans were then made for transmission from aircraft. A 100-mc receiver was designed and built. By May 1943 satisfactory PPI reproduction had been received at the East Boston Airport through relay radar in an airplane flying over the island of Nantucket at 10,000 feet.

At this time the radio link was reliable for about 50 miles. Shortly thereafter, in July 1943, the relay radar (AN/APS-14) was demon-

strated to naval officers at the East Boston Airport; a short film illustrating the system was prepared for COMINCH, which resulted in a request that the reliable range be extended to 100 miles or more. This was done.[a]

8.1.4 Organization of Project Cadillac [AEW]

Since subsequent production had not been decided upon at the end of December 1943, Division 14 asked that the relay-radar project be terminated. A month later, however, the U. S. Navy proposed a project to develop an *airborne early-warning* [AEW] system, incorporating a high-powered relay-radar device. The AEW project was then developed under RL code name of Project Cadillac.

The basic idea for Cadillac (extending the ship search antenna into the air) was simple enough. Achieving a workable system, however, was one of the most complex and difficult developmental problems attacked by the laboratory. The project was not only the largest in the history of the laboratory, but was of a new order of magnitude. In addition to engineering the complicated airborne system, an equally complicated shipboard system was required. So too was identification (IFF) equipment, test equipment, and a suitable voice communication system. In short, several types of electronic equipment, integrated into a system, were needed in the shortest possible time.

The Cadillac Project was first proposed in February 1944. After a series of conferences between representatives of BuOrd and MIT-RL, the U. S. Navy in April 1944 formally requested the NDRC to establish the project. In March 1945, just thirteen months after the first request, the first production system was delivered to the Navy.

The Cadillac production achievement was made possible, of course, by the scale of the cooperative effort. A large proportion of the members of nine of the laboratory's eleven divisions worked on the problem. The Bureau of Aeronautics, the Bureau of Ships, the Naval Aircraft Modification Center at Philadelphia, the Naval Research Laboratory, several Navy contractors, and a number of Radiation Laboratory subcontractors all contributed substantially to the equipment as it finally evolved. The scope of Project Cadillac at the laboratory is indicated by the fact that direct outside purchases for the project (not including large stockroom withdrawals) constituted 12 per cent of the total expenditures of the laboratory for materials and services for the entire five years of its existence. At the peak of the program, during the summer of 1945, approximately 20 per cent of the time of all the laboratory's technical staff members working on specific projects was spent on Cadillac. Navy personnel at the laboratory who were an integral part of the laboratory program reached a total of 160 officers and men.

[a]The National Broadcasting Company collaborated with MIT-RL in the early relay-radar development under an OSRD contract negotiated with RCA.

8.2 AEW CADILLAC I SYSTEM

8.2.1 System Components

The AEW Cadillac I system as it reached the fleet was in two basically separate sections: an airborne section, carried in a modified torpedo bomber, and a shipboard section for the presentation in visual form of the information relayed from the airplane. The complexity of both these sections was an outstanding aspect of the project.

Airborne System

The airplane, a TBM-3, was redesigned to carry the estimated 2,300 lb of equipment. The Naval Aircraft Modification Center [NAMC] undertook to adapt the plane and to conduct the necessary wind tunnel and flight tests. An 8-ft diameter bulbous radome was mounted between the aircraft's wheels to house the radar antenna. The ball turret, armor and armament, including the torpedo bay, were removed. Two additional tail stabilizers, a high-power supply operated by the engine, substantial modifications to the interior of the plane, and the mounting of nine different antennas at various locations on the wings, tail, and fuselage completed the plane modifications.

Radar Equipment. The radar equipment, AN/APS-20, operated at 10 cm with a peak power output of 1 megawatt and a 2-μsec pulse. The heart of the airborne section was a complex

synchronizer and a radar receiver with many new features. The airborne section also included the IFF interrogator-response, AN/APX-13. This was designed with the highest available peak power (2 kw) and most sensitive receiver in any airborne IFF development, to make possible the identification of targets on both of the standard Navy A and G bands at ranges comparable to the detection ranges of the radar equipment. The relay-radar transmitter, AN/ART-22, which was based upon the earlier laboratory project, broadcast, on any of several channels around 300 mc as selected, both radar and IFF information for reception by the shipboard section. Both the IFF and relay equipment were synchronized by the radar synchronizer, which also coded their outputs prior to relaying so as to "get through" interference or enemy jamming. A modified flux gate compass used to orient the radar information, a new type radio-control receiver (AN/ARW-35) making possible control of functions of the airborne equipment from the shipboard section, a relay system (AN/ARC-18) for relaying voice communication between ships and planes or other ships over the horizon, and the standard IFF transponder, voice communication equipment, radio altimeter, and homing receiver completed the airborne electronic gear.

Shipboard System

Any ship equipped with the shipboard section of AEW could, if within relay range, receive and display the information relayed from a plane. The shipboard section of AEW was also composed of several different devices, depending upon the requirements of the particular installation. The relay receiving equipment used either an omnidirectional or a horizontal diversity receiving system to pick up the information broadcast by the relay transmitter in the plane. Adjustable band-pass tuning cavities in the antenna line, and line filters for all other shipboard systems which transmitted side band energy on the relay frequency, were developed to minimize interference with the relay reception. The relay information, after it had been decoded by the complex and precision-adjusted decoder, was piped to two, three, or more PPI's located usually in the ship's *combat information center* [CIC].

Coordination of Airborne and Shipboard Systems

The picture on each indicating scope could be expanded in various ways. Facilities were devised so that the AEW airplane's motion could be eliminated and the picture centered on the receiving ship. Another innovation of the indicating system was the delayed PPI (also available in the plane) by which any 20-mile region of the main PPI picture could be expanded for detailed examination over the complete face of the tube.

A transponder beacon (YQ) of the Black Maria type responded in code on the IFF G band to interrogation from the plane, making possible identification of the receiving ship in the midst of other shipping. Interrogation could be radio-controlled from the ship and was accomplished by the coincident reception of 10-cm radiation from the airborne radar and G-band reception from the airborne IFF transmitter; or, if so desired, by coincident reception of the 10-cm radiation and a trigger signal transmitted over the radar relay link. A radio control-transmitter (AN/ARW-34) and standard voice communication equipment completed the shipboard electronic equipment.

8.2.2 Development of Cadillac I

Experimental Systems

To speed the development of a coordinated system, a ground radar set which simulated at lower power the projected AEW radar performance was established on Mount Cadillac, near Bar Harbor, Maine, where it operated for several months. Five complete air and ship AEW experimental systems were planned and constructed. The first airborne section was completed and flown in August 1944. The other four airborne sections, each improved somewhat over the one preceding it, followed at intervals of about a month. Shipboard sections were completed at the same rate, though started approximately one month later.

Organization. The AEW organization began in rather modest terms. W. P. Dyke, earlier the project engineer for ASG and ASD-1, was put in charge. Somewhat independent investigations of various aspects of the system were initiated in the transmitter division and receiver division

groups concerned. However, by May 1944, when acceptance of the project was recommended to NDRC by Division 14, a complete group organization was established in the laboratory.

Demonstration of AEW System. In October 1944 the first full-scale demonstration of the AEW system was given to a large group of Navy and Army leaders. For two weeks preceding the demonstration, two eight-hour shifts of personnel operated at the Bedford Airport to get 2 planes and 1 shipboard set into good operating condition. Although briefly plagued by aircraft engine trouble, the demonstration was successful; indeed, many laboratory members felt that it was too successful, since temporarily thereafter the urgent requests of the leaders of other projects for more personnel were not met.

8.2.3 Flight Testing

Bedford Trials

Starting with the first AEW-equipped plane whose radar operated reasonably well on its first flight in August 1944, continuous flight testing of AEW was carried on from the Bedford Airport until the end of World War II. Three experimental planes were eventually fitted out at Bedford. A fourth set was kept operating on the bench to try out new ideas on the ground, and also to serve as a spare, the components of which could be substituted at short notice for defective components in the planes. The first two experimental shipboard systems were also set up at Bedford and operated from there for many months. The third shipboard set, scheduled for Navy trials at Brigantine, New Jersey, was put into operation during December 1944 in MIT Building 20 in order to simulate more closely the heavy interference conditions expected in actual operation.

Results of Tests

To the dismay of the research workers, the complex system jammed itself; that is, interference was so bad that rotational data, transmitted by a double-pulsed code over the relay link, was almost completely jammed. Under the threat of possible failure for the program, however, a triple-pulsed coding system was devised and incorporated by around-the-clock work into all experimental synchronizers, relay receivers, and decoders. With many misgivings on the part of the engineers because of inadequate testing of this change, the third shipboard experimental set (SX-3) and the second airplane with AX-3 were shipped to Brigantine for the U. S. Navy trials about the first of January 1945, only two weeks behind schedule. Fortunately, the new coding system performed well.

During the hectic month of December 1944, the project engineer, W. P. Dyke, contracted an illness which made him unavailable for the duration of the AEW program. Unfortunately just at this time the U. S. Navy's pressure for early production deliveries increased. At a meeting in early December called by the Deputy Chief of Naval Operation (Air), the fleet's great need for AEW to combat low-flying planes and the Kamikaze attacks was officially disclosed. An overriding priority was added to the already top position of AEW in the electronics field. The Navy made available to the laboratory crews of officers, technicians, and draftsmen as fast as they could be assimilated. A special air transport service to facilitate deliveries of parts and personnel transportation was also set up by the Navy.

8.2.4 Production

Organization

In July 1944, before the first of the experimental models of AEW had even been flown, the importance of solving the early-warning problem had increased to such an extent that the Navy officially confirmed its earlier indication through NDRC that the MIT-RL and RCC undertake production of forty complete systems. Production planning and a number of large production subcontracts were immediately started, thus making the program truly "crash," with research, development, and production proceeding concurrently.

In order to achieve the coordination necessary for engineering, production, and delivery by RCC and the 30-odd major and multitudinous minor subcontractors of the laboratory, responsibility for this phase of the activity was largely delegated to R. J. Woodrow. C. M. Kelly, previously in charge of radar research and development, was designated the production engineer for the airborne section. A. C. Byers, in addition

to his duties as project engineer on other shipboard research and development, was chosen as the project engineer for the shipboard section of AEW. Weekly meetings were initiated with RCC in November 1944; close liaison was maintained with the laboratory subcontractors and many of their engineers spent a substantial portion of their time in Cambridge.

PRODUCTION SCHEDULING

It might appear impossible to schedule research and development in any detail; if the component parts and steps to be taken were known in advance, no research and development would be necessary. However a rather unorthodox, and to a certain extent backward, process of scheduling was attempted on the five AEW experimental systems. The estimates, based on previous experience of the Division 14 heads and group leaders concerned, were combined to give target dates for the delivery of each system. Then as designs crystallized and construction began, more detailed target dates for components and subcomponents were projected backwards from the system target dates.

Bottlenecks were thus discovered, and additional effort was concentrated on them by increasing personnel or expediting critical procurement items, by special attention in the shop, or by any other shortcuts that could be devised. Although the original target dates were missed by times ranging from two weeks for the first system to two months for the fifth (which had many features not originally contemplated), the results were far better than most people had expected. The scheduling procedure used is believed to be the only type generally practicable for research and development; even with it, results would have been poor had the project not had a high priority.

DESIGN CHANGES

Since research and development were proceeding in parallel with production, a very flexible method for incorporating changes was essential. A number of target dates for final freezing of design were set, each one advanced over the previous date; but actually there never was a final "freeze" date, but instead, a progressive elimination of the number of modifications to be made in designs which were in various stages of production.

DELIVERY SCHEDULING

The original production schedule proposed to the Bureau of Aeronautics in June 1944 prior to the formal request for production, was to start deliveries with two complete systems in February 1945. In November 1944 a revised schedule was presented which called for the delivery of 1 system in March 1945, followed by 4 in April and approximately 8 per month thereafter. Although very great efforts were later made to advance this schedule, the final deliveries, except for items subsequently added to the system, for the most part conformed to this delivery date.

TYPE TESTING

The fourth of the five experimental airborne and shipboard sections of AEW built at the laboratory were scheduled to go to RCC as prototype units and to serve as the first complete test bench system into which early production components could be substituted and tested. It had been hoped that, prior to delivery to RCC, these units could be type tested for altitude, temperature, humidity, and vibration. However, the pressure of time and the delays in delivery of adequate test apparatus made it impossible to test more than a few of the critical components. To supplement these tests, complete type tests were run on one of two extra systems constructed. Several necessary modifications were revealed by these tests and modification kits were prepared and distributed.

PERFORMANCE TESTING

Performance testing of each production component as it came off the production line was handled by complete and in some cases elaborate test procedures. Following the individual component tests, all the critical components of the system were assembled at RCC and tested in complete bench systems, of which two and the elements of a third were eventually established. This was a quite radical departure from previous radar production practices, but proved necessary because the space, facilities, and personnel available were inadequate for the assembly and test of all the components of each of the 40 systems at the same time. Such a procedure also made it possible to test and deliver in advance those airborne components requiring the longest time for installation in the planes.

Maintenance Program

In view of the complexity of the Cadillac system (the airborne and shipboard sections each contained approximately two hundred vacuum tubes not counting those in the standardized units) a comprehensive maintenance program was planned, and at the Navy's request, the laboratory presented in July 1944 complete recommendations for maintenance after installation. These recommendations included the spare parts to be furnished, a tentative list of the test equipment believed necessary, the complement of maintenance and operational personnel which should be trained, and the importance of having a complete bench test system of the airborne section, and a stand-by shipboard section aboard each carrier equipped.

Spare Parts. Between the time that these recommendations were prepared and the time of final installation and use, a year of many developments intervened. To provide greater flexibility, each equipment was provided with enough spare parts to insure approximately one year's operation. Seventy per cent of the test equipment originally proposed was either modified or replaced by other items.

Instruction Manuals. It was obvious from the start of the AEW project that such complex equipment would require comprehensive instructions for maintenance and operation. MIT-RL's publications group (Group 35.2) and a subcontractor, the Jordanoff Aviation Company, prepared the text and illustrations for the 820-page airborne and 570-page shipboard maintenance manuals. Some writing and a substantial editing job remained, which were handled by the staffs of the airborne and shipboard production engineers and by Lieut. Robert Kellner of the Navy. Preliminary handbooks to cover the maintenance of the experimental models during Navy trials served as prototypes for the final manuals. Owing to the large number of modifications ultimately made in the production systems, final shipboard instruction manuals were not available for most of the training stages and the first several installations, so that a sufficient quantity of interim handbooks were hectographed for these purposes. Handbooks of instruction had also to be prepared and published for 12 of the 18 test instruments supplied by MIT-RL and RCC.

8.2.5 U. S. Navy Trials

Center of Operation

Navy trials of the experimental AEW systems had been contemplated early in the program; these eventually included not only operations at the CIC Group Training Center, Brigantine, New Jersey, but also installation and operation of the equipment on board the carrier USS *Ranger*.

Reorganization of Project

The third airborne and shipboard experimental sections of AEW, following the flight tests at Cambridge previously described, were put into operation at Brigantine during the first part of January 1945. Many problems, some foreseen and others not, were almost immediately encountered. To accelerate their solution, a substantial reorganization of the project at the laboratory was made about the first of February 1945. The new organization operated essentially as a separate laboratory division known as Project Cadillac. J. B. Wiesner, project engineer, was in charge. He was assisted by R. Rollefson, project engineer for the airborne section, and R. E. Meagher, project engineer for the shipboard section. R. J. Woodrow continued as associate project engineer for production.

Project Cadillac coordinators were appointed in the office of CNO and in BuAer and BuShips. BuAer in particular assigned a substantial staff to the project.

Incorporation of Modifications

Even before the Brigantine tests were completed, most of the improvements recommended were well underway and being tested at Bedford. Modifications were incorporated in the shipboard relay receiver and decoder to improve their performance under conditions of interference. NRL, which had previously collaborated in the solution of mutual interference problems in the airplane, worked out the design of filters for other types of shipboard electronic equipment to prevent their transmitting appreciable amounts of energy at the relay frequency. Special anticlutter circuits were developed for the radar receiver to facilitate the distinguishing of signals through the clutter of echoes at close ranges from the surface of the sea.

Sea Trials

While the Brigantine trials were still underway, the equipment for sea trials aboard the USS *Ranger* was made ready and shipped to the West Coast. When the planes joined the carrier in April 1945, the installation was essentially complete and tests started almost immediately. The *Ranger* trials lasted for two months, and appeared to establish the value of AEW beyond question. Following close upon the end of the war, at least two carriers, the *Enterprise* and the *Bunker Hill*, made trial cruises during which AEW was used.

Performance Data

During the trials of the AEW Cadillac I system, much data on performance were collected. It was found that single aircraft of torpedo bomber size, flying at 500 ft, can be consistently detected at ranges of 45 to 70 miles with the AEW plane flying at 2,000- to 5,000-ft altitudes. This is twice the range of the best shipboard radar system on similar targets. Groups of 6 to 14 planes at 500 ft were detected at ranges varying from 60 to 120 miles, or two to four times the range of shipboard sets. Surface vessels of destroyer size or larger can be detected at 200 miles with the AEW plane flying at 20,000 ft, increasing by a factor of six the previously available range. The relay equipment proved reliable out to 45 miles from the receiving ship, thus making possible a further extension of the detection range in the direction of the AEW plane.

8.3 AEW CADILLAC II SYSTEM

8.3.1 Initiation of Program

In June 1945, while the Cadillac I program was at its peak, reports from the fleet indicated the need for the type of long-range reconnaissance, warning, and control made available by AEW, but in locations unsuitable to the operation of ships having AEW shipboard equipment. Upon request from the Navy to NDRC, MIT-RL initiated the Cadillac II program. This program contemplated the development and production of the necessary equipment for an airborne *combat information center* [CIC] in a four-engine bomber. Such a system had been considered much earlier, but MIT-RL and Project Cadillac were already so heavily engaged that it required an expression of the top priority of the program before it could be undertaken.

8.3.2 Design of Cadillac II

As conceived almost from the start, Cadillac II embraced the installation of all the previously developed Cadillac I airborne equipment plus a much increased complement of Navy-furnished communications gear. The new element in the system consisted of the CIC equipment, which was installed in the completely remodeled bomb bay of the plane. Large 12-in. off-center PPI's, equipment for ground-stabilizing the PPI presentation, and various associated apparatus were the major new contributions of MIT-RL. Plotting boards and most of the nonelectronic accessories for the CIC were developed and produced by the special devices division of BuAer. Modifications of the planes and installation of the equipment were again handled by NAMU.

8.3.3 Development and Production

When Cadillac II was initiated, the construction of 11 complete systems was contemplated, for which 11 sets of the Cadillac I equipment were to be diverted. The quantity was progressively increased to 13, then 17, and finally 25; this was eventually cut back to 17 at the end of the war.

Many of the same problems of development, testing, and production that were encountered in Cadillac I also appeared in Cadillac II, but to meet the very tight schedule (and since the scope of the second program was by dollar cost only a fifth of the former) substantially all the production was done at MIT-RL using MIT-RL and U. S. Navy personnel. Deliveries of the 17 systems started in August and were complete by the end of October 1945.

In addition to the development and production of the 17 CIC indicator systems (AN/APA-53) plus spares and instruction manuals, Cadillac II also included the establishment at the laboratory of a complete trainer for the system installed in a B-17 fuselage. Simulated data of the radar and IFF performance was fed into the radar indicators by a basic trainer developed earlier as a result of a Navy request to NDRC. Shortly after the end of the war the first completely equipped plane was ready to fly.

8.3.4 Applications of Cadillac II

The Cadillac II program opened up a new field for operational and tactical use. The obvious possibilities of control of a fleet of aircraft from one or more airborne control centers could have revolutionized large air operations, and, as ramifications of the original program, several other developments resulted which could have further extended these possibilities. An *airborne moving-target indication* [AMTI] system had been flown and showed much promise of discriminating between moving targets and echoes from the ground or sea so that AEW operation over land had important possibilities. Designs had been completed and contracts let for complete airborne CIC facilities for simultaneous and independent control of several combat air patrols. Means for determining the altitude of aircraft targets were likewise under study. However, the possibilities of Cadillac II, like those of Cadillac I (and like all the most advanced wartime developments, for that matter) fortunately had no opportunity to be realized in World War II.

PART III

HARP–MATERIAL WITH ARTIFICIALLY CONSTRUCTED DIELECTRIC CONSTANT AND PERMEABILITY

Chapter 9

DEVELOPMENT AND PRODUCTION PROCESSES

9.1 INTRODUCTION

9.1.1 Historical Survey

THE WORK reported in this part grew out of ideas which had been submitted to NDRC and the Radiation Laboratory at the Massachusetts Institute of Technology [MIT-RL] in the summer of 1941 by one of the authors.[a] Work was started at MIT-RL in December 1941 and was continued there under various organizational forms until the end of 1945 when it was transferred to the Naval Research Laboratory [NRL] under the direction of one of the authors.[b]

The practical aim was the production of technically useful thin layers which would reflect ultra high-frequency radio waves poorly. The work naturally divided itself into two parts: the discovery and study of physical principles which would lead to the satisfactory construction of such layers; and the various uses to which they might be put when obtained.

The physical principles were contained in a memorandum presented to MIT-RL suggesting the use of a medium of high dielectric constant and/or magnetic permeability, these properties being due to conducting (ferromagnetic) flakes suspended in a neutral organic binder. It will be shown below in detail why such a medium could be expected to have high electric and magnetic polarizability and how the possession of such a substance enables one to construct technically useful absorbing layers.[1-4]

It was obvious at the start of the work that such materials once obtained would have many useful applications. Protection against radio waves was desirable in many instruments and arrangements connected with friendly transmitters. It was similarly desirable as camouflage against enemy transmitters. Selectively absorbing layers could be used similarly for identification purposes; a simple reasoning given in Section 11.2.1 shows that every selectively absorbing layer can easily be transformed into a selectively transmitting layer, i.e., a selective filter. Chapter 12 of this report is devoted to a detailed discussion of various forms in which such applications can be made practical.

[a] O. Halpern.
[b] M. H. Johnson

9.1.2 Physical Concepts Underlying HARP

The idea of using suspended magnetic particles to obtain an artificially ferromagnetic body of high magnetic susceptibility has been attempted many times. The different and more favorable results obtained by the present method are due to a special feature which can be explained on the basis of simple electrostatic and magnetostatic analogies.

The a-c magnetic permeability of a powder is not only limited by hysteresis, eddy-current losses, magnetic relaxation, etc., but also mostly by the demagnetizing effect of the individual particles. This difficulty, for example, has been a dominant factor in the well-known work of the Bell Telephone Laboratories [BTL] staff; these engineers compressed and deformed the originally spheroidal particles to obtain shapes of smaller demagnetizing factors. As far as known, there have been no previous attempts to produce an artificial dielectric constant of large value by the aid of suspended particles. Since the discussion for the electric and the magnetic case is perfectly symmetrical, the treatment of the dielectric constant will be given first.

The depolarizing factor which is identical with the demagnetizing factor depends on the shape of the particle exclusively. Although the mathematical treatment is restricted to ellipsoids, shapes of practical interest can be approached as limiting cases.

It is well known that a plate-like ellipsoid shows the largest depolarizing factor if the electric vector is directed perpendicularly to the surface of the plate; the depolarizing factor becomes small if the electric vector lies in the plane of the plate. The very simple expedient suggested for the construction of media of high dielectric constant consisted in the use of flakes the short

dimension of which was very small compared to the long dimensions, and which were preferably oriented with one of their long dimensions parallel to the electric vector. Threads lying parallel to the electric vector would be similarly useful but suffer from the disadvantage that they cannot be produced as easily as flakes.

The result of the first experiment made with such flakes at MIT-RL showed the feasibility of these ideas. Commercial aluminum flake mixed with an organic liquid was spread on paper by a brush and allowed to dry. The thin layer of aluminum flake thus produced had a dielectric constant of about 500 in the wavelength region of 10 cm.

The problem of calculating the electric or magnetic susceptibilities of a medium thus composed is extremely difficult, if not almost impossible, at the present state of theoretical physics. The only available basis for an estimate is offered by the Lorenz-Lorentz formula which is known to be quite incorrect and to underrate the values obtained. This is particularly true here since the size of the constitutive particles is by no means small compared with their average separation so that the mutual interaction cannot even approximately be described as a dipole effect. The huge divergencies between the numbers given by Lorenz-Lorentz formula and the actual measurements may be illustrated by one sample which gave for the dielectric constant 165 and 2,700, respectively.

9.2 THEORY AND CHARACTERISTICS OF HARP

9.2.1 Introduction

From the discussion of Sections 9.1.1 and 9.1.2, it is clear that there are three essential elements in the fabrication of HARP, namely, the composition and geometrical properties of the conducting flakes which are used as pigment, the binder in which the flake is suspended, and the process for combining the flake and binder. These elements are the subject of Sections 9.2.2, 9.2.3, and 9.2.4. The concluding section deals in greater detail with the spraying process which has been developed to the point of production in a pilot plant.[5-20]

The electromagnetic behavior of HARP is characterized completely by its dielectric constant ϵ and its permeability μ. These quantities depend on all the parameters of the three elements mentioned above. Although the qualitative discussion of Sections 9.1.1 and 9.1.2 permits an estimate of the way ϵ and μ depend on these parameters, the estimates are necessarily rough. The mathematical difficulties of a quantitative theory have been mentioned. Consequently, the quantitative relationship between ϵ and μ and these parameters have been derived from experiment. The information is, however, rather incomplete partly because experiments were only conducted to determine data essential to problems at hand and partly because many of the factors in the fabricating processes were not brought under precise control.

9.2.2 Conducting Flakes

The materials from which conducting flakes are obtained have been either metals or some form of carbon. The intrinsic electrical properties of these materials are characterized by their conductivity and magnetic permeability. Ferromagnetic metals are used to impart permeability to the completed HARP film. The additional factors involved in their use will be discussed in the last paragraph of this section.

The factors, other than the intrinsic electrical properties of the conductor, which govern the dielectric constant and permeability of HARP, are the size and shape of the conducting particles. The size must be sufficiently small that the electromagnetic field extends throughout the interior of the particle and the shape must have a small depolarizing factor for the direction of the applied electric field. The small dimension of the metallic particles must be of the order of 1 micron or less for microwave applications whereas graphite or carbon particles may be much larger (in the ratio of the square root of the resistivities). These thickness values are set by the skin depth of the conductor in question. The shape of metallic particles has always been disklike rather than threadlike because the latter form is much more difficult to produce. Either form has a small depolarizing factor for an electric field parallel to the long dimension. Metallic

particles with an average diameter to thickness ratio from 15 to 70 have been used. The efficiency of the particles in imparting a dielectric constant to the HARP film increases very rapidly for increasing values of the diameter-to-thickness ratio.

Graphite in some forms has a natural disklike structure. Metallic particles on the other hand must be treated to produce the requisite shape. Either a hammer or a ball mill are used for this purpose. The ball mill is preferable because the resulting flake is much more uniform in size and shape. Nevertheless flake from a ball mill contains particles whose parameters vary by more than a factor 2. This distribution in size and shape is one of the reasons that an exact correlation has not been established between the particle parameters and the HARP properties.[c]

The conductivity determines the skin depth of a conductor at a given frequency; consequently, as the frequency is increased, the dielectric constant of HARP begins to decrease when the skin depth becomes of the order of the particle thickness. Thus, for microwave HARP, the real part of the dielectric constant is independent of the frequency for all lower frequencies. At a sufficiently high frequency the dielectric constant begins to decrease. The conductivity also influences the imaginary component of the dielectric constant for it determines the energy dissipation of currents which flow when the particles are polarized by the applied field. The losses are greater for conductors with low conductivity. Hence, the incorporation of carbon or graphite in HARP film increases the imaginary component of the dialectric constant.

The preparation of ferromagnetic flakes in general has a detrimental effect on the magnetic properties of the metal. Those metals and alloys with very high permeability are particularly sensitive to mechanical and heat treatment and therefore are most affected by the milling process. Efforts to restore the magnetic properties by annealing the flake have met with indifferent success because annealing at the required temperatures deforms the particles. Nevertheless, a number of HARP films fabricated from ferromagnetic metals suitable for resonant absorbers have shown permeabilities of about 2 at 10 cm and about 7 at 150 cm. Films have also been produced with permeabilities in the neighborhood of 20 at 150 cm. However, they had too great an absorption coefficient to be effective as resonant absorbers.

9.2.3 Binders

The binder of a HARP film is primarily a medium for supporting the metal flake. It is mainly responsible for the mechanical properties of the material. Its electrical characteristics also have some influence on the dielectric constant of HARP.

The binder must be of such a nature that the metallic flake can be used as a pigment. Hence, either organic compounds which may be dissolved or suspended in a liquid, or semi-liquid rubber compounds which set after moderate heat treatments have been used. Ceramic materials in which it is also possible to mix the metal particles before firing have not been tried because the flexibility of the HARP film is an important advantage in most applications. The choice of binder in the wide field indicated is dictated by a combination of mechanical and electrical considerations, as well as by the actual fabrication method.

Tough, flexible films containing a high percentage of metal can be produced from a number of organic polymers. The most successful of these have been artificial rubbers such as GR-S and neoprene. Films of excellent mechanical qualities have been made with neoprene and carbon black in the ratio 2 to 1 with metal concentrations (aluminum) in the neighborhood of 25%. Films of good mechanical quality have been formulated from GR-S with metal (aluminum) concentrations as high as 75%. These films withstood prolonged out-of-door exposures and were undamaged in severe accelerated rain tests on the camber surface of aircraft propellers. A thin nylon topcoat provides resistance to oil and similar liquids.

The bonding of the film to metal backing foil, usually 2-mil Al, has been most successfully accomplished by a Goodyear rubber cement with the trade name of Pliobond. The cement is

[c]Metallic flake has been obtained from many companies engaged in manufacturing metal powders. However, most of the experimental work on flake used for the HARP program was done at the Metals Disintegrating Company, Elizabeth, N. J.

sprayed on the foil and the film sprayed directly over it in this fabricating process. In other cases the cement is sprayed on the foil and the bond is set in a hot press. These bonds are almost as strong as the material itself. The metal backing is bonded to the surface to be covered by a pressure sensitive adhesive, L-115, manufactured by the B B Chemical Company. Bonds of adequate strength have thereby been obtained even when the covered surface is itself metal.

The principal effect of the binder on the electrical properties of HARP arises from dielectric loss in the binder. This contributes to the imaginary component of ϵ and is important in films whose absorption index must be kept low. In other cases the loss in the binder is used to effect the proper absorption index for a resonant absorber. Of the two binders mentioned above, GR-S has a very low loss so that the absorption in HARP fabricated from it is mainly due to the metal flakes. Neoprene, on the other hand, has a considerable dielectric loss which is enhanced by the addition of carbon. Absorption in HARP fabricated from it is almost entirely due to the binder.

9.2.4 Fabricating Processes

A number of fabricating processes for combining the flake and binder to produce a resulting film are available. They differ mainly in the degree of alignment of the metal flakes parallel to the surface of the film that can be achieved. They fall into two classes. In the first the mixture of flake and binder is effected in a liquid solution or suspension of the binder. The film is constructed of successive layers laid down by a knifing or spraying technique, the solvent being evaporated by drying each layer. When the film has been built to the proper thickness, it is cured at a temperature usually about 130 C to obtain a stable product. In the second class the metal is mixed with the flake in a rubber mill. The product is then calendered into thin sheets. The final product is obtained either by laminating the sheets to the desired thickness in a hot press or by forming a large block in the same manner from which the desired sheets are sliced.

The behavior of HARP with varying concentrations of metal is similar for all the fabricating processes. A typical example is shown in Figure 1. The index of refraction ($= \sqrt{\epsilon}$) has been plotted as the metal concentration, given as percentage by weight, is changed. In the lower part of the curve, clay has been added to the binder to keep the film from being excessively soft. Identical flake was used for all samples. It will be noted that the curve is at first approximately linear and rises very rapidly at the higher metal concentrations. The absorption index for refractive indices between 25 and 45 is approximately correct for resonant absorbers. For higher refractive indices it is too great while for lower refractive indices it is too small. Hence, for each binder and flake there is a region of refractive indices which are associated with the correct absorption index to give HARP suitable for a resonant absorber.

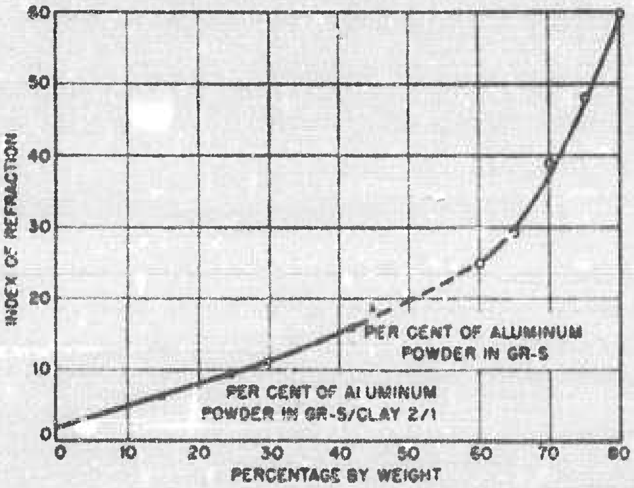

FIGURE 1. Variation of refractive index with metal concentration.

In processes of the first kind, a high degree of flake alignment is attained by depositing the film in successive layers. As the solvent evaporates, the surface tension aligns the particles parallel to the film. In addition to the theoretical considerations of Sections 9.1.1 and 9.1.2, very early experiments at MIT-RL showed the importance of this factor in imparting a high dielectric constant to HARP. For example, a flake and binder which yields $\epsilon = 2,500$ when fabricated by spraying may give a dielectric constant less than 100 when no effort is made to align the flake.

Of these processes, the knifing technique was first used to obtain considerable quantities of film. Each layer was deposited by a knife the height of which above a very flat piece of glass

was carefully controlled. By knifing successive coats at right angles a nondirectional film of high index was obtained. Although a substantial amount of film was produced in this way, no other method being available at the time, it is highly unsatisfactory as a production process, both from the standpoint of uniformity in the product and of cost. Much better films were obtained by knife-casting on a large wheel. However these films were necessarily directional in their properties, having a 30 per cent higher dielectric constant in the direction of the knife stroke.

A number of attempts were also made to knife-cast film on long sheets of cloth carried over rollers. This method also gave nonuniform materials which were highly directional. The method finally evolved to produce nondirectional film of uniform quality was that of spraying successive layers on a foil base. It will be more fully discussed in Section 9.2.5. In this process a system of electrical testing could be incorporated to control the production at various stages so that it was not necessary to keep the numerous variables of the process absolutely constant.

The second class of processes yields a much lower degree of flake alignment and is therefore useful for HARP of low refractive index. As the thicknesses are then much greater, all tolerances are correspondingly increased. If, in addition, the variable factors arising from solvents are removed by avoiding the use of solvents, the whole process can be sufficiently well controlled so that tests on a single sample of a batch suffice to determine the required thickness for the whole batch. This is essential for production by these processes as there is no simple method of adjusting the thickness after the film is formed.

The binder and pigment are generally mixed in a rubber mill and then calendered into sheets between 10 and 50 mils in thickness. Each sheet is quite directional with a higher dielectric constant along the length of the sheet. In the press-curing method these sheets are cross-laminated and press-cured to the proper thickness. In the slicing process the sheets are cross-laminated, or otherwise formed to reduce directionality and are press-cured in a large chase. The material is sliced from the block by a machine knife. Films of very uniform thickness have been made in this fashion. Plant trials in which 25 to 50 sq yd of HARP were fabricated indicate that this will be an entirely satisfactory production method for low-index HARP.

9.2.5 Pilot Plant Production

After the spraying method had proved successful on a small scale, a pilot plant for the production of HARP was assembled by the Du Pont Company at Newburgh, N. Y. It contained four essential elements: the spray machine and associated ventilating equipment, a belt dryer, curing ovens, and electrical test equipment. The cement composed of binder, solvent, and flake was prepared at another plant of the company.

A transverse DeVilbiss spraying machine was found to be very satisfactory. The gun traveled transversely over the panels to be sprayed at an adjustable height. When a proper spray pattern had been determined by varying the height and speed of the gun, the pressure at the gun, the speed at which the panels were carried under the gun, the viscosity of the spray fluid, etc., 20-mil films could be sprayed in about 30 coats the total thickness of which varied by less than a mil over the surface of the film.

The aluminum foil on which the film was sprayed was affixed to a sheetrock base to insure that the foil was perfectly flat. At the end of the process, the completed films were stripped from the base. The panels, 4 ft by 2 ft, were normally carried through the spraying cycles in pairs. After passing under the gun, the belt conveyor carried them through a dryer to remove the solvent before the next application. At the end of each cycle the panel was rotated through 90° to remove all trace of directionality in the final product. In the last few cycles, electrical tests for the resonant absorption were made to determine the point at which the process should stop to produce the requisite film. The testing was essential as the resonant wavelength, and consequently the thickness, had to be held to 1 per cent. After a panel had been sprayed to the proper thickness, it was subjected to a temperature cycle in the curing ovens. The curing temperatures required careful adjustment to yield a stable product. Small changes in the resonant wavelength of a film as a result of curing were known in advance so that the uncured panels

were adjusted to a thickness which would yield the required resonant wavelength after curing.

The capacity of this plant was limited by the drying cycle and the handling of the panels. It was operated on a 24-hour basis and could produce somewhat more than 1,000 sq yd a month. The plant was first used to produce some 1,500 sq yd of S-band film.[d] It was later operated under a Navy contract to produce about 2,500 sq yd of X-band HARP and 600 sq yd of S-band HARP.

The Navy specifications, NAVAER-M-710/M-712, required that X-band HARP, designated as MX-410/AP, should have a power reflection coefficient less than 4 per cent over the wavelength band from 3.18 cm to 3.22 cm when tested at a 30° angle of incidence. The film was approximately 20 mils thick. The specification NAVAER M-710/M-711 for S-band HARP, designated as MX-355/AP, required that the power reflection coefficient be less than 5 per cent over the wavelength band from 9.04 cm to 9.16 cm when tested at a 30° angle of incidence. The film was about 50 mils thick.

[d] Under OSRD Contract OEMsr-1199.

Chapter 10

ELECTROMAGNETIC PROPERTIES OF HARP

10.1 PROPAGATION IN A DIELECTRIC AND PERMEABLE MEDIUM

THE PROPAGATION OF WAVES through a medium with a dielectric constant ϵ and magnetic permeability μ is governed by Maxwell's equations. As all the phenomena discussed in this report are stationary in type, the field quantities vary with time as $e^{i\omega t}$ where $\omega = 2\pi\nu$, ν being the frequency of the field. Thus the electric field is $\mathbf{E}e^{i\omega t}$, the electric induction is $\mathbf{D}e^{i\omega t}$, the magnetic field is $\mathbf{H}e^{i\omega t}$, the magnetic induction is $\mathbf{B}e^{i\omega t}$, and the current density is $\mathbf{u}e^{i\omega t}$. Under these conditions Maxwell's equations are:

$$\operatorname{div} \mathbf{D} = 0, \tag{1}$$

$$\operatorname{div} \mathbf{B} = 0, \tag{2}$$

$$\mathbf{curl}\, \mathbf{E} = -ik_0\mathbf{B}\,, \tag{3}$$

$$\mathbf{curl}\, \mathbf{H} = \frac{4\pi}{c}\mathbf{u} + ik_0\mathbf{D}\,. \tag{4}$$

where

$$k_0 = \frac{\omega}{c} = \frac{2\pi}{\lambda_0}\,.$$

To these equations must be added the constitutive relations

$$\mathbf{u} = \sigma\mathbf{E}, \tag{5}$$

$$\mathbf{D} = \epsilon_0\mathbf{E}, \tag{6}$$

$$\mathbf{B} = \mu\mathbf{H}, \tag{7}$$

where σ is the conductivity of the medium. It is convenient to eliminate equation (5) immediately by writing the fourth Maxwell equation (4) as

$$\mathbf{curl}\, \mathbf{H} = ik_0\mathbf{D}, \tag{8}$$

and

$$\mathbf{D} = \epsilon\mathbf{E}, \tag{9}$$

where[a]

$$\epsilon = \epsilon_0 - \frac{2i\sigma}{\gamma}. \tag{10}$$

Wave propagation given by the solutions of these equations is essentially determined by the quantities ϵ and μ.

[a] In the case of Cu at a frequency of 3×10^9c ($\lambda_0 = 10$ cm), the imaginary part of ϵ is 3.42×10^8.

The medium will be assumed uniform. Inhomogeneous media can be treated as several uniform regions separated by boundaries at which ϵ and μ discontinuously change in value.

The dielectric constant and magnetic permeability are in general complex. Thus

$$\epsilon = \epsilon_r - i\epsilon_i, \tag{11}$$

$$\mu = \mu_r - i\mu_i. \tag{12}$$

ϵ_i and μ_i must be positive if the corresponding terms in the equation for the Poynting vector represent energy dissipation. The imaginary part of ϵ may arise from conduction currents through the medium and from dielectric loss. The imaginary part of μ is introduced to account for a high-frequency magnetic loss, distinct from hysteresis and eddy-current losses, which is known to exist. It is tentatively ascribed to a relaxation time for magnetization.

In an isotropic medium simple elimination leads to the following propagation equation which is satisfied by all components of **E** and **H**.

$$\nabla^2\psi + \epsilon\mu k_0^2\psi = 0. \tag{13}$$

Plane waves of the type $\exp(-i\mathbf{k}\cdot\mathbf{r})$ are solutions of this equation where

$$k = k_0\sqrt{\epsilon\mu}\,. \tag{14}$$

If the propagation vector is along the positive z axis, the electric and magnetic fields are given by

$$\mathbf{E} = E_y = Ae^{-ikz}, \tag{15}$$

$$\mathbf{H} = H_x = -A\sqrt{\frac{\epsilon}{\mu}}\,e^{-ikz}. \tag{16}$$

This is a damped wave whose wavelength is determined by the real part of the propagation constant and whose damping constant is determined by the imaginary part.

$$k = k_r - ik_i \tag{17}$$

$$k_r = k_0\sqrt{|\epsilon|\,|\mu|}\cos\left[\tfrac{1}{2}\tan^{-1}\frac{\epsilon_i}{\epsilon_r} + \tfrac{1}{2}\tan^{-1}\frac{\mu_i}{\mu_r}\right] \tag{18}$$

$$k_i = k_0\sqrt{|\epsilon|\,|\mu|}\sin\left[\tfrac{1}{2}\tan^{-1}\frac{\epsilon_i}{\epsilon_r} + \tfrac{1}{2}\tan^{-1}\frac{\mu_i}{\mu_r}\right]. \tag{19}$$

It will be noted that positive ϵ_i and μ_i are required in order that the wave diminish in amplitude for increasing positive values of z.

It has been previously observed that HARP materials contain metal flakes which are aligned to a greater or less degree with the surface of the material. Consequently the electrical properities are anisotropic; ϵ and μ must be considered tensor quantities. Because the same metallic flakes give HARP its dielectric as well as its magnetic properties, the principal axes of the ϵ and μ tensors necessarily coincide. Furthermore, in most cases, two of the three principal components of ϵ and of μ are equal. Let x, y, and z be the principal axes of the ϵ and μ tensors and let ϵ_1, μ_1 be components of the tensors along the x and y axes while ϵ_2, μ_2 are the components along the z axis. Equations (6) and (7) may be written

$$\begin{aligned} D_x &= \epsilon_1 E_x, \\ D_y &= \epsilon_1 E_y, \\ D_z &= \epsilon_2 E_z. \end{aligned} \tag{20}$$

$$\begin{aligned} B_x &= \mu_1 H_x, \\ B_y &= \mu_1 H_y, \\ B_z &= \mu_2 H_z. \end{aligned} \tag{21}$$

For subsequent use it is only necessary to treat the case in which E_z or H_z is zero. In the first case the solution to the above equations is given by

$$\mathbf{E} = E_y = A e^{-i(k_x x + k_z z)}, \tag{22}$$

$$H_x = -A \frac{k_z}{\mu_1 k_0} e^{-i(k_x x + k_z z)}, \tag{23}$$

$$H_z = A \frac{k_x}{\mu_2 k_0} e^{-i(k_x x + k_z z)}, \tag{24}$$

where the components of the propagation vector satisfy the relation

$$k_z^2 + \frac{\mu_2}{\mu_1} k_x^2 = \epsilon_1 \mu_2 k_0^2. \tag{25}$$

In the second case the solution is given by

$$E_x = A e^{-i(k_x x + k_z z)}, \tag{26}$$

$$E_z = -A \frac{\epsilon_1 k_x}{\epsilon_2 k_z} e^{-i(k_x x + k_z z)}, \tag{27}$$

$$\mathbf{H} = H_y = A \frac{\epsilon_1 k_0}{k_z} e^{-i(k_x x + k_z z)}, \tag{28}$$

where the components of the propagation vector satisfy the relation

$$k_z^2 + \frac{\epsilon_2}{\epsilon_1} k_x^2 = \epsilon_2 \mu_1 k_0^2. \tag{29}$$

In the application to be discussed later, k_x^2 is small compared with k_z^2. As a result k_z is very nearly given by $k_0\sqrt{\epsilon_1\mu_1}$ and the effects arising from anisotropy in ϵ and μ are all of second order.

10.3 ELECTROMAGNETIC MEASUREMENTS ON THIN SAMPLES[30]

The determination of the dielectric constant and magnetic permeability of HARP materials can be conveniently effected by mounting thin samples in a waveguide or coaxial line. A slotted section is used to measure the phase and amplitude of the wave reflected by the sample. If the line is shorted by a metallic plug a quarter wavelength behind the sample, the sample is in a region of strong electric field and weak magnetic field. The phase and amplitude of the reflected wave then depend only on the dielectric properties of the HARP material. If the line is shorted directly behind the sample, the sample is in a region of strong magnetic field and weak electric field. The phase and amplitude of the reflected wave then depend only on the magnetic properties of the HARP material. A detailed discussion of this method of determining ϵ and μ follows.

Consider first the propagation in a coaxial line whose inner conductor of radius a and outer of radius b are supposed ideal conductors. The boundary conditions on these surfaces are that the tangential component of $\mathbf{E}$ and the normal component of $\mathbf{H}$ be zero. If the cylindrical coordinates z, r, and ϕ be used, the solution of equations (1-7) which correspond to the normal type of coaxial transmission are

$$\mathbf{E} = E_r = \frac{A}{r}\left(e^{ikz} + \alpha' e^{-ikz}\right), \tag{30}$$

$$\mathbf{H} = H_\phi = -\frac{A}{r}\sqrt{\frac{\epsilon}{\mu}}\left(e^{ikz} - \alpha' e^{-ikz}\right), \tag{31}$$

where k is given by equation (13). It is conve-

nient to introduce the ratio of E_r to H_ϕ. Thus

$$\zeta(z) = \frac{E_r}{H_\phi} = -\sqrt{\frac{\mu}{\epsilon}}\,\frac{e^{ikz} + \alpha' e^{-ikz}}{e^{ikz} - \alpha' e^{-ikz}}. \quad (32)$$

The boundary conditions at the surface between two sections of the line filled with different media (tangential components of E and H continuous) can now be replaced by the condition that ζ be continuous across this boundary.

Let the sample have one boundary at $z = 0$, the other at $z = -d$. Furthermore let

$$E_r = \frac{1}{r}\, e^{ik_0z}$$

be the incident wave falling on the sample from the left while

$$E_r = \frac{\alpha}{r}\, e^{-ik_0z}$$

is the wave reflected to the right and α is the amplitude reflection coefficient. Then

$$\zeta(0) = -\frac{1+\alpha}{1-\alpha}. \quad (33)$$

Hence the amplitude and phase of the reflected wave can easily be determined as soon as $\zeta(0)$ is known.

The two cases of interest are $\zeta(-d) = 0$ and $\zeta(-d) = \infty$. The first condition corresponds to a short circuit directly behind the sample while the second corresponds to a short circuit $\lambda/4$ behind the sample. In the first case

$$e^{-ikd} + \alpha' e^{ikd} = 0\,,$$

so that

$$\zeta(0) = -\sqrt{\frac{\mu}{\epsilon}}\,\frac{1 - e^{-2ikd}}{1 + e^{-2ikd}} \approx -i\mu k_0 d\,. \quad (34)$$

In the second case

$$e^{ikd} - \alpha' e^{ikd} = 0\,,$$

so that

$$\zeta(0) = -\sqrt{\frac{\mu}{\epsilon}}\,\frac{1 + e^{-2ikd}}{1 - e^{-2ikd}} = \frac{-1}{i\epsilon k_0 d}. \quad (35)$$

In both cases use has been made of the fact that the sample is thin, $(kd)^2 \ll 1$. If α is determined by a measurement of the phase and amplitude of the reflected wave, equations (33), (34), and (35) may be used to find ϵ and μ. It will be noted that if $\epsilon_i = \mu_i = 0$, then $|\alpha| = 1$.

In practice the quantities measured are the shift in position l of the minima of the standing wave system and the voltage standing wave ratio x when the sample is introduced into the line. Let

$$\Delta = \frac{2\pi l}{\lambda_0}. \quad (36)$$

Remembering that the voltage standing wave ratio is given by $\dfrac{1+|\alpha|}{1-|\alpha|}$ and that phase shift of the reflected wave is given by the argument of α, it is found that

$$\epsilon_r - 1 = \frac{l}{d}, \quad (37)$$

$$\epsilon_i = \frac{1}{k_0 d x}, \quad (38)$$

in case the short circuit is $\lambda/4$ behind the sample. In the magnetic case

$$\mu_r - 1 = \frac{l}{d}, \quad (39)$$

$$\mu_i = \frac{1}{x k_0 d}. \quad (40)$$

If the phase shift is quite large, the following more accurate formulas should be used in the dielectric case.

$$\epsilon_r - 1 = \frac{1}{k_0 d}\tan\Delta\,, \quad (41)$$

$$\epsilon_i = \frac{1}{x k_0 d}(1 + \tan^2\Delta)\,. \quad (42)$$

In a rectangular waveguide of width a the solution corresponding to the lowest mode of propagation is given by

$$E_x = A \sin\frac{\pi y}{a}\,(e^{ik'z} + \alpha' e^{-ik'z})\,, \quad (43)$$

$$H_y = -A\sqrt{\frac{\epsilon}{\mu}\left[1 - \frac{1}{\epsilon\mu}\left(\frac{\pi}{k_0 a}\right)^2\right]}\cdot \sin\frac{\pi y}{a}\,(e^{ik'z} - \alpha' e^{-ik'z})\,, \quad (44)$$

$$H_z = A\,\frac{\pi}{i\mu k_0}\cos\frac{\pi y}{a}\,(e^{ik'z} + \alpha' e^{-ik'z})\,, \quad (45)$$

where

$$k'^2 = \epsilon\mu k_0^2 - \left(\frac{\pi}{a}\right)^2. \quad (46)$$

The expression for ζ is now

$$\zeta(z) = \sqrt{\frac{\mu}{\epsilon\left[1 - \frac{1}{\epsilon\mu}\left(\frac{\pi}{k_0 a}\right)^2\right]}}\, \frac{e^{ik'z} + \alpha' e^{-ik'z}}{e^{ik'z} - \alpha' e^{-ik'z}}. \quad (47)$$

For the solution in HARP material ϵ and μ are always sufficiently large that the term $(\pi/a)^2$ can be neglected in equations (46) and (47). The equation for ζ becomes identical with equation (32) for the coaxial line. In parts of the guide filled by air or material of very low dielectric constant, $(\pi/a)^2$ cannot be neglected and gives rise to the well-known difference between free-space and guide wavelength. Then equation (33) must be replaced by

$$\zeta(0) = \frac{-1}{\sqrt{1 - \left(\frac{\pi}{k_0 a}\right)^2}}\, \frac{1+\alpha}{1-\alpha}. \quad (48)$$

Combining equation (48) with equation (34) and expressing the results in terms of l and x in the same manner as before, it is found that for the magnetic case equations (39) and (40) still remain valid if the guide wavelength is used throughout in place of the free-space wavelength, similarly expressions for ϵ_r and ϵ_i, equations (41) and (42), may be used provided that in addition to this change ϵ_r and ϵ_i are multiplied by the factor $[1-(\pi/k_0 a)^2]^{-1}$.

Table 1 shows the calculation of dielectric constants made from measurements at 10 cm in a coaxial line on typical samples. The first two samples are of HARP materials while the second two are binders consisting of GR-S and clay (sample 3) and GR-S and ZnO (sample 4).

Measurements similar to these have also been made in a rectangular waveguide. The waveguide is superior to the coaxial line in that differences in the dielectric constant for different orientations of the electric vector in the plane of the sample can be measured. The coaxial line measurements always yield the dielectric constant averaged over all orientations in this plane.

In general, measurements of the dielectric constant in thin samples cease to be accurate (errors of 10 per cent or greater) when ϵ_r exceeds 2,000. As a quarter wavelength is then about 20 mils, the construction of ledges to support the sample in such a way as not to affect the measurement is prohibitively difficult. Furthermore the presence of air gaps of the order of 1 mil between the boundary of the sample and the metal walls can cause large distortions in the electric field. In these respects the waveguide and coaxial methods are approximately equally good. The fact that rings and ledges can be more accurately turned on a lathe for coaxial fittings is roughly compensated by the fact that the irregularities in the waveguide are introduced in a region where the electric field is not so intense.

TABLE 1. Calculation of dielectric constants from 10-cm measurements in a coaxial line.

Sample	Thickness in mils	$\frac{1}{k_0 d}$	Power SWR in db	$\frac{1}{x}$	l in cm	tan Δ	ϵ_r	ϵ_i
709-3	4.0	156.0	46.0	0.0050	2.414	18.7	2,900.0	270.0
2076-3	2.5	250.0	29.6	0.034	1.092	0.8	200.0	12.0
2109-1	84.0	7.4	44.0	0.006	0.73	0.48	3.56	0.05
2109-5	62.0	10.0	34.0	0.020	0.65	0.43	4.3	0.24

Chapter 11

THEORY AND APPLICATIONS OF RESONANT ABSORBENT LAYERS

11.1 THEORY OF RESONANT ABSORBING LAYERS

It has already been noted in the introduction that the realization of a quarter wavelength absorbing layer in a practical form depends on the use of material with high refractive index. Since this is the most important type of absorber, a detailed discussion of its properties is given in this chapter. In addition this study yields another method for determining ϵ and μ which does not suffer from the limitations mentioned at the end of Chapter 10.

The theory of an absorbing layer which is an odd multiple of a quarter wavelength in thickness is most easily developed for an open space. When the general results, including the behavior for waves incident at an oblique angle, have been obtained, the necessary modifications for an absorber in a closed space (waveguide or coaxial line) can be simply made.

As in Section 10.1, let the boundaries of the HARP layer be at $z = 0$ and $z = -d$. At $z = -d$ let there be a perfectly reflecting metal plane. The solution of Maxwell's equations for an incident wave normal to the layer in the medium is

$$\mathbf{E} = E_y = A(e^{ikz} + \alpha' e^{-ikz}) . \tag{1}$$

$$\mathbf{H} = H_x = -A\sqrt{\frac{\epsilon}{\mu}}(e^{ikz} - \alpha' e^{-ikz}) . \tag{2}$$

Introducing $\zeta(z)$ as in equation (32) Chapter 10,

$$\zeta(z) = \frac{E_y}{H_x} = -\sqrt{\frac{\epsilon}{\mu}}\,\frac{e^{ikz} + \alpha' e^{-ikz}}{e^{ikz} - \alpha' e^{-ikz}} \quad 0 \geq z \geq -d \tag{3}$$

$$\zeta(z) = -\frac{e^{ik_0z} + \alpha e^{-ik_0z}}{e^{ik_0z} - \alpha e^{-ik_0z}} \quad z \geq 0 . \tag{4}$$

In these equations k is given by equation (14) Chapter 10. The boundary conditions are that $\zeta(-d) = 0$ and ζ is continuous at $z = 0$. The first condition gives

$$e^{-ikd} + \alpha' e^{+ikd} = 0 . \tag{5}$$

The second becomes

$$\frac{1+\alpha}{1-\alpha} = -\zeta(0) = \sqrt{\frac{\mu}{\epsilon}}\,\frac{1 - e^{-2ikd}}{1 + e^{-2ikd}} \tag{6}$$

α is again the amplitude reflection coefficient.

Before examining the resonant case, it may be noted that when $\epsilon = \mu$

$$\alpha = -e^{-2ikd} . \tag{7}$$

Hence if $k_i d$ is large, α becomes zero. Therefore if a medium for which $\epsilon = \mu$ could be constructed with a reasonably large value of ϵ_r, it could be used for a practical absorbing layer which was not resonant. The band width would be determined by the extent to which ϵ and μ varied with frequency.

It is clear from equation (6) that, in the phase and amplitude of the reflected wave, the wavelength and thickness of the layer enter explicitly only in the combination $k_0 d$. Over the width of a resonant absorption band, ϵ and μ change inappreciably. Consequently the resonance curves depend only on λ_0 and d, through the ratio d/λ_0. It will be seen later that over wider frequency ranges the reflection coefficient no longer depends solely on this ratio because the permeability in magnetic materials changes considerably with frequency.

Equation (6) may be solved for α. Let

$$\gamma = \sqrt{\frac{\mu}{\epsilon}} = \gamma_r + i\gamma_i . \tag{8}$$

Expressing k in terms of its real and imaginary part and setting $\tan k_r d = 1/\phi$ equation (6) yields

$$\alpha = \frac{\phi(\gamma_r \tanh k_i d - 1) - \gamma_i + i\,[\phi\gamma_i \tanh k_i d + \gamma_r - \tanh k_i d]}{\phi(\gamma_r \tanh k_i d + 1) - \gamma_i + i\,[\phi\gamma_i \tanh k_i d + \gamma_r + \tanh k_i d]} . \tag{9}$$

Consider first the case that ϵ and μ have the same phase angle so that $\gamma_i = 0$. Equation (9)

can then be written

$$|\alpha|^2 = \frac{\phi^2(\gamma \tanh k_r d - 1)^2 + (\gamma - \tanh k_r d)^2}{\phi^2(\gamma \tanh k_r d + 1)^2 + (\gamma + \tanh k_r d)^2} \quad (10)$$

$$\arg \alpha = \tan^{-1}\left[\frac{\gamma - \tanh k_r d}{\phi(\gamma \tanh k_r d - 1)}\right] - \tan^{-1}\left[\frac{\gamma + \tanh k_r d}{\phi(\gamma \tanh k_r d + 1)}\right]. \quad (11)$$

Hence $|\alpha|^2$ has its minimum value, $|\alpha_{min}|$, at $\phi = 0$. At the minimum

$$|\alpha_{min}| = \left|\frac{\gamma - \tanh k_r d}{\gamma + \tanh k_r d}\right| = \left|\frac{1-g}{1+g}\right|, \quad (12)$$

where

$$g = \frac{\tanh k_r d}{\gamma} \quad (13)$$

$$\arg \alpha_{min} = \begin{cases} 0 & g < 1 \\ -\pi & g > 1 \end{cases}. \quad (14)$$

The conditions for complete absorption are therefore

$$k_r d = (2n+1)\frac{\pi}{2} \quad n = 0, 1, \cdots \quad (15)$$

$$\tanh k_r d = \gamma \quad g = 1. \quad (16)$$

It will be noted if the absorption is not complete, the phase of the reflected wave at the minimum is 0 or $-\pi$. In the first case corresponding to a too small loss in the layer, the electric field has a loop at the surface of the layer. In the second case corresponding to a too large loss, it has a node at the surface. The voltage standing wave ratio x is given by

$$x = g \text{ for } g > 1$$
$$x = \frac{1}{g} \text{ for } g < 1. \quad (17)$$

Which form of equation (17) is applicable can be determined by measuring the phase of the reflected wave. Hence measurement of the standing wave ratio, the phase of the reflected wave and the frequency at resonance, fix the values of $\tanh k_r d/\gamma$ and k_r.

Determination of the phase of the reflected wave is difficult in some experimental arrangements. An alternative method to indicate whether the loss of the material is greater or less than that for a matching layer ($g = 1$) is possible by comparing a quarter and three-quarter wave layer of the same material. Let x_0, d_0, and g_0 refer to the quarter wave layer while x_1, d_1, and g_1 refer to the three-quarter wave layer. Then

$$\tanh k_r d_1 = \tanh 3k_r d_0 = \tanh k_r d_0 \frac{3 + \tanh^2 k_r d_0}{1 + 3\tanh^2 k_r d_0}. \quad (18)$$

First suppose that $g_0 > 1$, then since $\tanh 3k_r d_0$ is necessarily greater than $\tanh k_r d_0$ it follows

$$x_1 = \frac{\tanh 3k_r d_0}{\gamma} = x_0 \frac{3 + \tanh^2 k_r d_0}{1 + 3\tanh^2 k_r d_0}. \quad (19)$$

In most cases $(k_r d_0)^2 \ll 1$ so that the standing wave ratio for the three-quarter wave layer is just three times as great as for the quarter wave layer. Hence it is always greater than 3. Next suppose $g_0 < 1$, then

$$g_1 = \frac{1}{x_0} \frac{3 + \tanh^2 k_r d_0}{1 + 3\tanh^2 k_r d_0}. \quad (20)$$

If $(k_r d_0)^2 \ll 1$, x_1 will be equal to $3/x_0$ if x_0 is less than 3, and equal to $x_0/3$ if x_0 is greater than 3.

It can therefore be concluded that if $x_0 < 3$ and $x_1 > 3$, the loss in the material is greater than the matching loss while if $x_0 < 3$ and $x_1 < 3$, the loss is less than the matching loss. In the latter case the standing wave ratios become equal when the loss is such that $\tanh k_r d_0 = \sqrt{3}\gamma$. Finally if $x_0 > 3$, the loss is less than the matching loss if $x_1 < x_0$ and greater if $x_1 > x_0$.

To examine the behavior near resonance it is necessary to know how ϕ depends on the wavelength. If λ_0 is the resonant wavelength and λ_0' is a nearby wavelength, let

$$\Delta\lambda = \lambda_0' - \lambda_0 \quad (21)$$

$$\Delta k_r = k_r' - k_r. \quad (22)$$

Then

$$k_r' = k_r\left(1 + \frac{\Delta k_r}{k_r}\right) = k_r\left(1 - \frac{\Delta\lambda}{\lambda_0}\right). \quad (23)$$

In equation (23) use has been made of the fact that ϵ and μ do not vary appreciably in the wavelength range $\Delta\lambda$. Then

$$\begin{aligned}\phi &= \cot k_r' d \\ &= \cot\left[(2n+1)\left(1 - \frac{\Delta\lambda}{\lambda_0}\right)\right]\frac{\pi}{2} \\ &= \tan\left[(2n+1)\frac{\pi\Delta\lambda}{2\lambda_0}\right]. \end{aligned} \quad (24)$$

For every value of $\Delta\lambda$ the corresponding value of ϕ is readily determined from equations (21, 22, 23). In fact in most cases of interest $\phi^2 \ll 1$ so that

$$\phi = (2n+1)\frac{\pi\Delta\lambda}{2\lambda_0}. \tag{25}$$

Using equation (10) and the definition of g in equation (13) the power reflection coefficient $|\alpha|^2$ can be written

$$|\alpha|^2 = \frac{(\phi/\gamma)^2(\gamma^2 g - 1)^2 + (1-g)^2}{(\phi/\gamma)^2(\gamma^2 g + 1)^2 + (1+g)^2}. \tag{26}$$

Since γ and g are slowly changing functions of frequency, the wavelength dependence of $|\alpha|^2$ is essentially determined by ϕ/γ. In view of equations (8) and (25)

$$\phi/\gamma = (2n+1)\frac{\pi}{2}\frac{\Delta\lambda}{\lambda_0}\sqrt{\frac{\epsilon}{\mu}}. \tag{27}$$

From this expression it is clear that in a layer of given material and with a given value of $\Delta\lambda$, ϕ/γ is three times as large for a three-quarter wave as for a quarter wave layer. Hence the band width of a three-quarter wave layer is smaller than that of a quarter layer. The precise ratio depends on the definition of band width because the absorption curves have different shapes and different minimum values in the two cases. By a similar argument the band width is in general smaller for larger values of $\sqrt{\epsilon}$ and larger for larger values of $\sqrt{\mu}$. In most cases the term $\gamma^2 g$ can be neglected so that equation (26) becomes

$$|\alpha|^2 = \frac{(\phi/\gamma)^2 + (g-1)^2}{(\phi/\gamma)^2 + (g+1)^2}. \tag{28}$$

In the next section the manner in which this equation is used to determine μ is described.

It is also possible to determine γ from the shape of the absorption curve in another way. The points of inflection in the graph of α^2 against ϕ can be found by setting the second derivative of equation (10) equal to zero and solving the resulting equation for ϕ. The following relation is obtained

$$\phi = \pm\frac{1}{\sqrt{3}}\frac{\gamma(1+g)}{1+\gamma^2 g}. \tag{29}$$

This value of ϕ can be determined experimentally as well as g. Equation (29) can then be used to find γ.

In case $\gamma_i \neq 0$, it may be assumed small in all practical cases, or more precisely $\gamma_i^2 \ll \gamma_r^2$ so that $|\gamma| = \gamma_r$. This is equivalent to assuming, except when $\epsilon = \mu$ that $\epsilon_i^2 \ll \epsilon_r^2$ and $\mu_i^2 \ll \mu_r^2$ so that $|\epsilon| = \epsilon_r$ and $|\mu| = \mu_r$. It follows that $k_i^2 \ll k_r^2$ and $|k| = k_r$. Equations (18) and (19) become

$$k_r = k_0\sqrt{\epsilon_r\mu_r} \tag{30}$$

$$k_i = k_0\sqrt{\epsilon_r\mu_r}\,\tfrac{1}{2}\left(\frac{\epsilon_i}{\epsilon_r} + \frac{\mu_i}{\mu_r}\right). \tag{31}$$

Now if $g = \tanh k_i d/\gamma_r$, equation (9) may be rewritten without making any approximations as

$$|\alpha|^2 = \frac{[\phi(\gamma_r^2 g - 1) - \gamma_i]^2 + \gamma_r^2[\phi\gamma_i g + 1 - g]^2}{[\phi(\gamma_r^2 g + 1) - \gamma_i]^2 + \gamma_r^2[\phi\gamma_i g + 1 + g]^2} \tag{32}$$

$$\arg\alpha = \tan^{-1}\left[\frac{\gamma_r(\phi\gamma_i g + 1 - g)}{\phi(\gamma_r^2 g - 1) - \gamma_i}\right] - \tan^{-1}\left[\frac{\gamma_r(\phi\gamma_i g + 1 + g)}{\phi(\gamma^2 g + 1) - \gamma_i}\right]. \tag{33}$$

It is evident that the minimum value of $|\alpha|^2$ no longer occurs at $\phi = 0$. Setting $(d/d\phi)\,|\alpha|^2 = 0$, it is found to occur for values of ϕ satisfying

$$-\phi_m^2 + 4\phi_m\frac{\gamma_r^2 g(1-\gamma^2)}{\gamma_i(1+\gamma^2\gamma_r^2 g^2)} + \frac{\gamma^2 + \gamma_r^2 g^2}{1+\gamma^2\gamma^2 g} = 0.$$

To the first order in γ_i

$$\phi_m = -\frac{\gamma_i}{4}\frac{1+g^2}{g(1-\gamma_r^2)}. \tag{34}$$

Then if g is not close to 1, the terms in γ_i^2 are negligible and

$$|\alpha_m|^2 = \left(\frac{1-g}{1+g}\right)^2. \tag{35}$$

However, if g is nearly unity,

$$|\alpha_m|^2 = \tfrac{1}{2}\left[(1-g)^2 + \frac{1}{4}\frac{\gamma_i^2}{\gamma_r^2}\right]. \tag{36}$$

Consequently the minimum value of the power reflection coefficient can never be less than $\gamma_i^2/8\gamma_r^2$. For most purposes this is not a serious limitation as the reflection coefficient can be made smaller than 1/125 even though $\gamma_i/\gamma_r = \frac{1}{4}$.

The resonant wavelength, defined as the value

at which the reflection coefficient is a minimum, is now given by

$$k_r d = (2n+1)\frac{\pi}{2} + \frac{\gamma_i}{4}\,\frac{1+g^2}{g(1-\gamma_r^2)}. \qquad (37)$$

Usually equation (15) can be used to find k_r. Equation (37) can then be used to obtain a more accurate value after γ_i has been determined.

From equation (33) it is apparent that the phase of the reflected wave is no longer 0 or π at $\phi = 0$. Setting arg α equals to zero, equation (33) yields

$$\phi_p = \frac{\gamma_i g}{1-\gamma_r^2 g}. \qquad (38)$$

A quantity which is immediately determined experimentally is the difference in wavelength between the resonance point and the point at which the phase of the reflected wave passes through 0 or π. From equations (34) and (38) this difference is

$$\phi_p - \phi_m = \gamma_i\left[\frac{g}{1-\gamma_r^2 g} + \frac{1+g^2}{4g(1-\gamma_r^2)}\right]. \qquad (39)$$

If the resonant point is at shorter wavelength than the point of zero phase, γ_i is positive. If it is at longer wavelength, γ_i is negative.

Examination of equation (33) at $\phi = 0$ shows that the phase of the reflected wave is 0 or π under exactly the same conditions as before. Hence equation (17) still applies whether γ_i is positive or negative and the ratio tanh $k_i d/\gamma_r$ can be determined as before. In view of the above mentioned approximations this ratio is

$$g \simeq \frac{k_i d}{\gamma_r} \simeq \frac{k_i}{\gamma_r k_r}(2n+1)\frac{\pi}{2}$$

$$= \sqrt{\frac{\epsilon_r}{\mu_r}}\left(\frac{\epsilon_i}{\epsilon_r} + \frac{\mu_i}{\mu_r}\right)(2n+1)\frac{\pi}{4}. \qquad (40)$$

Thus if γ_r and k_r are determined as before, thereby fixing ϵ_r and μ_r, equation (40) yields the value of $\epsilon_i/\epsilon_r + \mu_i/\mu_r$. Similarly

$$\gamma_i = \sqrt{\frac{\mu_r}{\epsilon_r}}\sin\left[\tfrac{1}{2}\tan^{-1}\frac{\mu_i}{\mu_r} - \tfrac{1}{2}\tan^{-1}\frac{\epsilon_i}{\epsilon_r}\right]$$

$$= \frac{1}{2}\sqrt{\frac{\mu_r}{\epsilon_r}}\left(\frac{\mu_i}{\mu_r} - \frac{\epsilon_i}{\epsilon_r}\right). \qquad (41)$$

Thus equation (39) can be used to find $\mu_i/\mu_r - \epsilon_i/\epsilon_r$.

The nature of the changes in these results when the incident wave is no longer normal can be seen without calculation. In materials of high refractive index the angle of refraction given by Snell's law is small for all angles of incidence. Consequently, the path difference between the ray reflected at the front surface and the ray reflected by the metal backing is nearly independent of the angle of incidence. The resonant wavelength of the layer will therefore be nearly correctly given by equation (15). The requisite damping of the internal wave, however, will be altered because the reflection coefficient at the front surface depends on the angle of incidence as well as the polarization of the incident wave. If the reflection coefficient is higher, smaller attenuation of the internal ray is required to produce cancellation of the reflected and emergent rays. If it is lower, larger attenuation is required. Hence, equation (16) will be altered in such a way that tanh $k_i d$ is smaller than γ when the incident wave is polarized with its electric vector perpendicular to the plane of incidence and tanh $k_i d$ is larger than γ when the incident electric vector is in the plane of incidence. In the latter case the required attenuation is infinite at Brewster's angle as the reflection coefficient of the front surface vanishes for this angle and polarization. Brewster's angle for materials of high refractive index is close to grazing incidence.

As before let $z = 0$ be the front surface of the HARP layer and $z = -d$ be the back surface at which there is a perfect metallic reflecting plane. Let the xz plane be the plane of incidence and let the direction cosines of the incident wave be $-\sin\theta$ and $\cos\theta$. The incident and reflected waves then contain the coordinates in the form $e^{-ik_0 x\sin\theta}\,(e^{ik_0 z\cos\theta} + \alpha e^{-ik_0 z\cos\theta})$ while the internal wave contains the coordinates in the form $e^{-ik_x x}$ $(e^{ik_z z} + \alpha' e^{-ik_z z})$. These solutions are obtained from equations (15), (22-25), and (26-29) of Chapter 10. The boundary condition at $z = 0$ must hold over the entire xy plane. Therefore the exponential terms containing x must be identical for the two solutions. Hence

$$k_x = k_0\sin\theta. \qquad (42)$$

Equations (25, 29) of Chapter 10 can now be written to give the propagation vector in the layer

$$k_z = k_0\sqrt{\epsilon_1\mu_1}\sqrt{1-\frac{\sin^2\theta}{\epsilon_1\mu_2}}, \tag{43}$$

$$k_z = k_0\sqrt{\epsilon_1\mu_1}\sqrt{1-\frac{\sin^2\theta}{\epsilon_2\mu_1}}. \tag{44}$$

The second radical gives the correction to k_z resulting from oblique incidence. For polarization perpendicular to the plane of incidence, equation (43), ϵ_1 is usually so large that the correction is negligible. For polarization in the plane of incidence, equation (44), ϵ_2 may be much smaller so that the correction is appreciable and gives rise to a shift in the resonant frequency as the angle of incidence is changed.

For polarization perpendicular to the plane of incidence the solutions of Maxwell's equations in the layer area

$$E_y = Ae^{-ik_x x}\left(e^{ik_z z}+\alpha' e^{-ik_z z}\right), \tag{45}$$

$$H_x = \frac{k_z}{\mu_1 k_0}Ae^{-ik_x x}\left(e^{ik_z z}-\alpha' e^{-ik_z z}\right), \tag{46}$$

$$H_z = \frac{k_x}{\mu_2 k_0}Ae^{-ik_x x}\left(e^{ik_z z}+\alpha' e^{-ik_z z}\right). \tag{47}$$

The solutions in air are obtained by setting $A = 1$, $k_x = k_0\sin\theta$, $k_z = k_0\cos\theta$, and $\mu_1 = \mu_2 = 1$. Introducing the quantity $\zeta(z)$

$$\zeta(z) = \frac{E_y}{H_x} = \frac{\mu_1 k_0}{k_z}\frac{e^{ik_z z}+\alpha' e^{-ik_z z}}{e^{ik_z z}-\alpha' e^{-ik_z z}} \quad 0\geq z\geq -d, \tag{48}$$

$$\zeta(z) = \frac{1}{\cos\theta}\frac{e^{ik_0 z\cos\theta}+\alpha e^{-ik_0 z\cos\theta}}{e^{ik_0 z\cos\theta}-\alpha e^{-ik_0 z\cos\theta}} \quad z\geq 0. \tag{49}$$

The boundary conditions that $\zeta(-d) = 0$ gives

$$\alpha' = -e^{-2ik_z d}. \tag{50}$$

The boundary condition at $z = 0$ becomes

$$\frac{\mu_1 k_0}{k_z}\frac{1-e^{-2ik_z d}}{1+e^{-2ik_z d}} = \zeta(0) = \frac{1}{\cos\theta}\frac{1+\alpha}{1-\alpha}. \tag{51}$$

Comparison of equation (51) with equation (6) shows that the previous discussion of resonant layers is applicable in its entirety provided the following substitutions are made: k must be replaced by k_z as given in equation (43); the quantity γ must be replaced by

$$\gamma_\perp = \frac{\mu_1 k_0}{k_z}\cos\theta = \cos\theta\sqrt{\frac{\mu_1}{\epsilon_1}}\sqrt{1-\frac{\sin^2\theta}{\epsilon_1\mu_2}}. \tag{52}$$

It is evident that the resonance condition, equation (15), is unaltered while equation (16) requires that tanh $k_1 d$ be reduced by the factor $\cos\theta$.

For the polarization in the plane of incidence, the solutions in the layer are:

$$E_x = Ae^{-ik_x x}\left(e^{ik_z z}+\alpha' e^{-ik_z z}\right), \tag{53}$$

$$E_z = \frac{\epsilon_1 k_x}{\epsilon_2 k_z}Ae^{-ik_x x}\left(e^{ik_z z}-\alpha' e^{-ik_z z}\right), \tag{54}$$

$$H_y = -\frac{\epsilon_1 k_0}{k_z}Ae^{-ik_x x}\left(e^{ik_z z}-\alpha' e^{-ik_z z}\right). \tag{55}$$

In air the solutions are obtained from equations (53-55) by setting $A = 1$, $k_x = k_0\sin\theta$, $k_z = k_0\cos\theta$ and $\epsilon_1 = \epsilon_2 = 1$. Introducing the quantity ζ,

$$\zeta(z) = \frac{E_x}{H_y} = -\frac{k_z}{\epsilon_1 k_0}\frac{e^{ik_z z}+\alpha' e^{-ik_z z}}{e^{ik_z z}-\alpha' e^{-ik_z z}} \quad 0\geq z\geq -d. \tag{56}$$

$$\zeta(z) = -\cos\theta\frac{e^{ik_0 z\cos\theta}+\alpha e^{-ik_0 z\cos\theta}}{e^{ik_0 z\cos\theta}-\alpha e^{-ik_0 z\cos\theta}} \quad z\geq 0. \tag{57}$$

The boundary condition that $\zeta(-d) = 0$ gives

$$\alpha' = -e^{-2ik_z d}. \tag{58}$$

The boundary condition at $z = 0$ becomes

$$\frac{k_z}{\epsilon_1 k_0}\frac{1-e^{-2ik_z d}}{1+e^{-2ik_z d}} = -\zeta(0) = \cos\theta\frac{1+\alpha}{1-\alpha}. \tag{59}$$

Hence, for this polarization the previous discussion is also applicable provided that the following substitutions are made: k must be replaced by k_z as given by equation (44); the quantity γ must be replaced by

$$\gamma_\parallel = \frac{k_z}{\epsilon_1 k_0\cos\theta} = \frac{1}{\cos\theta}\sqrt{\frac{\mu_1}{\epsilon_1}}\sqrt{1-\frac{\sin^2\theta}{\epsilon_2\mu_1}}. \tag{60}$$

It is evident that the resonance condition, equation (15), is substantially unaltered while equation (16) requires that tanh $k_1 d$ be now increased by the factor $1/\cos\theta$. Brewster's angle is determined from equation (59) by putting the exponential terms equal to zero ($\alpha' = 0$) and

setting the resulting expression for α equal to zero. It is thus found to be the angle at which $\gamma_{\parallel} = 1$ and is given by:

$$\tan \theta = \sqrt{\frac{\epsilon_2 (\epsilon_1 - \mu_1)}{\epsilon_2 \mu_1 - 1}}. \tag{60a}$$

The resonance condition, equation (16), requires $\tanh k_t d = 1$ which can only be satisfied if the attenuation in the layer is infinite ($k_t d = \infty$).

It is instructive to compare the behavior of a given layer at a given angle of incidence for the two states of polarization. Consider first a layer which has a matching loss at normal incidence ($\tanh k_t d = \gamma$). The second radical in equations (43) and (44) gives a slight shift in the resonant wavelength of the layer, the shift for the perpendicular polarization being immeasurably small while that for the parallel polarization may be several per cent. Otherwise, the presence of this radical in the succeeding equations gives no measurable effect. Then from equations (52) and (60)

$$\gamma_{\perp} = \gamma \cos \theta \quad \gamma_{\parallel} = \frac{\gamma}{\cos \theta}. \tag{61}$$

It follows that

$$g_{\parallel} = \frac{\tanh k_t d}{\gamma_{\parallel}} = \cos \theta, \tag{62}$$

$$g_{\perp} = \frac{\tanh k_t d}{\gamma_{\perp}} = \frac{1}{\cos \theta}. \tag{63}$$

Consequently $x_{\parallel} = x_{\perp}$. Thus, at resonance, the reflected wave has the same amplitude but opposite phase for the two states of polarization. The equality of the standing wave ratio for both states of polarization provides a convenient and sensitive method of testing a layer for the critical loss.

Consider a layer in which the loss is not equal to the matching value. Then

$$g_{\parallel} = \frac{\tanh k_t d}{\gamma} \cos \theta, \tag{64}$$

$$g_{\perp} = \frac{\tanh k_t d}{\gamma \cos \theta}. \tag{65}$$

If $\tanh k_t d/\gamma > 1$ (loss exceeds the critical value for normal incidence), $g_{\parallel}$ decreases as θ increases, reaching the value 1 at

$$\cos \theta_{\parallel} = \frac{\gamma}{\tanh k_t d}, \tag{66}$$

while $g_{\perp}$ increases in value. Thus the standing wave ratio approaches unity for the parallel polarization while it becomes larger for the perpendicular polarization. Similarly if $\tanh k_t d/\gamma < 1$, $g_{\perp}$ decreases as θ increases, reaching the value 1 at

$$\cos \theta_{\perp} = \frac{\tanh k_t d}{\gamma}, \tag{67}$$

while $g_{\parallel}$ increases. The standing wave ratio approaches 1 for the perpendicular polarization while it becomes large for the parallel polarization. This reversal of behavior for the two states of polarization supplies a very simple means of determining whether the loss in a given layer is too high or too low. It may be noted that

$$\begin{aligned} \sqrt{x_{\parallel} x_{\perp}} &= \frac{\tanh k_t d}{\gamma} \quad \text{if } \theta < \theta_{\parallel}, \\ &= \frac{\gamma}{\tanh k_t d} \quad \text{if } \theta < \theta_{\perp}. \end{aligned} \tag{68}$$

The substitution of $\gamma_{\parallel}$ and $\gamma_{\perp}$ for γ also affects the band widths at different angles of incidence. The right hand member of equation (27) is multiplied by $\cos \theta$ for parallel polarization and by $1/\cos \theta$ for perpendicular polarization. Hence the band width increases in the former and decreases in the latter case as the angle of incidence is increased. As grazing incidence is approached, the band width becomes very great for parallel polarization and very small for perpendicular polarization.

The application of the previous results to a coaxial line is immediate. Since the electromagnetic wave in a coaxial line is transverse, all the results for a resonant layer with the incident wave normal to the layer are valid here.

In a waveguide of the usual type the electric field is transverse while the magnetic field has a longitudinal component. The solution may always be considered as a sum of two waves making an angle θ with the z axis where, equations (43-45, 47),

$$\sin \theta = \frac{\pi}{k_0 a}. \tag{69}$$

In the treatment for oblique incidence the amplitude, α, of the reflected wave is independent of the sign of θ. Hence, the formula for α applies to any combination of the waves with θ and with

$-\theta$. Therefore, the previous discussion for a resonant layer with polarization perpendicular to the plane of incidence and for the angle of incidence given by equation (69) is valid for a waveguide.

11.2 EXPERIMENTAL RESONANT LAYERS

Experimental data[a] has been obtained for a wide variety of HARP films from a wavelength of 1 cm to 2 m. The largest portion of the data has been in the wavelength region from 3 cm to 13 cm. A great variety of materials have been tested including many binders, different types of metal flake and film produced by many different fabricating techniques. However the data on magnetic films is relatively meager because the pressure of other developments did not permit much diversion of effort to this phase of the work until the concluding months of the war. Before summarizing the experimental information, a brief description of the measuring apparatus is in order.

Measurements on HARP films in open space have been successfully made in the microwave region. The equipment is in principle very simple. The output of a signal generator energizes a highly directional antenna such as a parabolic reflector or a horn-type radiator. The radiation is reflected from a metal plate whose linear dimensions must be several wavelengths, into a second directional antenna. A receiver, fed from the second antenna, is so arranged that its output meter indicates the received energy. The sample to be tested which must be geometrically identical with the metal plate is substituted for the plate. The ratio of received energies gives directly the power reflection coefficient of the sample.

In the actual equipment the signal generator is modulated at an audio frequency. The receiver consists of a bolometer, an audio-frequency amplifier and an indicating meter. The bolometer is preferably a "barratter," i.e., a fine wire, which absorbs the high-frequency energy, connected in a simple bridge circuit. If care is taken that the audio-frequency amplifier is linear, the output meter readings are directly proportioned to the received energy. With the metal plate in place the gain of the amplifier is adjusted so that the output meter reads 100. Upon substitution of the sample, the meter reads directly the power reflection coefficient of the sample. If a crystal is used, care must be taken to select a crystal which gives a square law response at the power levels of interest or a calibration of the crystal must be made.

The horn-type antenna indicator has been found most convenient, particularly when mounted on a circular arch. A platform at the center of the circle is used to support the samples and the metal reference plates. Care must be taken that the angles of incidence and reflection from the sample are exactly equal and that the plane of the sample is exactly perpendicular to the bisector of the incident and reflected directions. Care must also be taken that the samples are perfectly flat. If small samples are being tested, absorbing screens should be placed over the portions of the pedestal supporting the sample which are illuminated by the incident radiation. With these precautions the above equipment has been successfully used at plants of the Du Pont Company to control the production of HARP materials.

For measurements made in a closed space, a slotted section of waveguide or coaxial line is used. The sample is mounted at the end of the line against a metal shorting plug. Care must be taken that there are no air gaps in back of the sample or at the surfaces of the sample for which there is a normal component of the electric field. This is extremely difficult to avoid when the sample has a high refractive index (>30). The measurement of the reflection coefficient is made in the standard way.

Typical behavior of HARP absorbers is shown in Figures 1 and 2. The first set of curves are for S-band samples, the second for X band. It will be observed that in the wide range of band widths represented the band width is roughly proportional to the thickness. The tabulated values of the refractive index are obtained from the resonant wavelength λ_0 by the relation,

$$N = \frac{\lambda_0}{4d}. \tag{70}$$

This equation follows immediately from equation (15), ($n = 0$) when it is remembered the refractive index is defined as $N = k_r/k_0 = \sqrt{\epsilon_r \mu_r}$.

[a]The experimental work for the HARP program was largely carried out by R. W. Wright.

To compare the experimental data with theory it is convenient to replot the absorption curve with $u = N\Delta\lambda/\lambda_0$ as abscissa. From equation (27)

$$\frac{\phi}{\gamma} = \frac{\pi}{2}\frac{N\Delta\lambda}{\mu_r\lambda_0} = \frac{\pi u}{2\mu_r}. \tag{71}$$

Then equation (28) with $g = 1$ becomes

$$|\alpha|^2 = \frac{\left(\frac{\pi u}{2\mu_r}\right)^2}{4 + \left(\frac{\pi u}{2\mu_r}\right)^2}. \tag{72}$$

The curve of this equation with $\mu_r = 1$ is the solid curve in Figures 3 and 4. The points shown in Figure 3 are taken from the curves of Figure 1 for S-band samples, while those in Figure 4 are taken from Figure 2 for X-band samples. All the X-band samples follow the theoretical curve

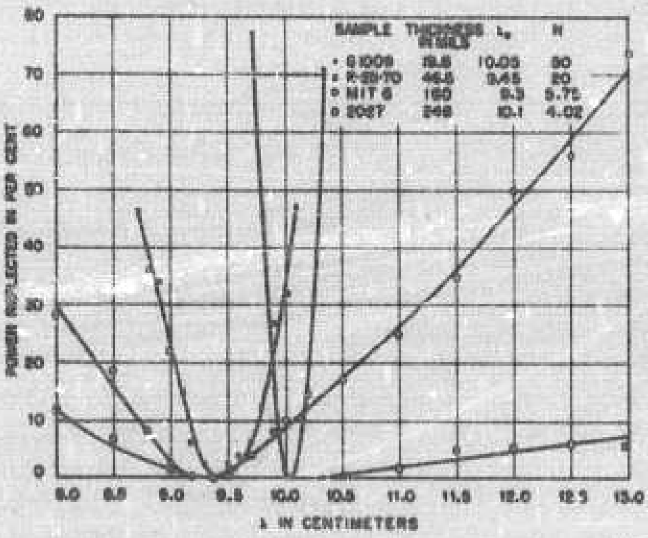

FIGURE 1. Absorption curves for typical S-band HARP samples.

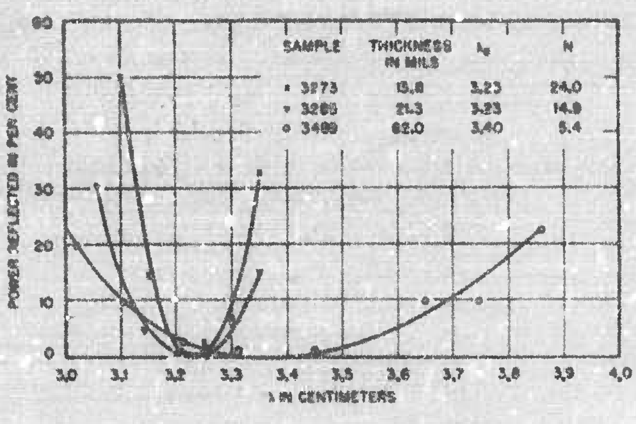

FIGURE 2. Absorption curves for X-band HARP samples.

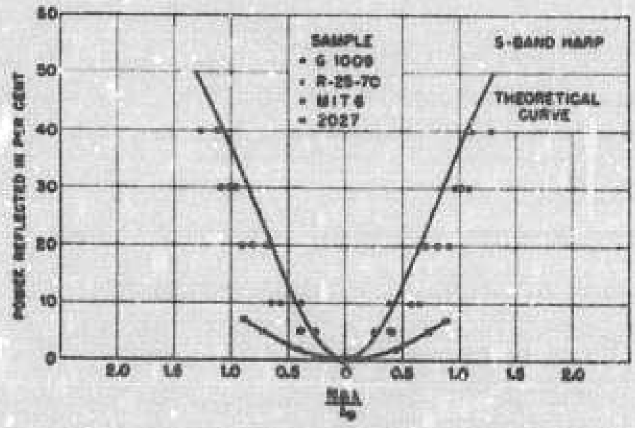

FIGURE 3. Comparison of theoretical and experimental absorption curves for S-band HARP.

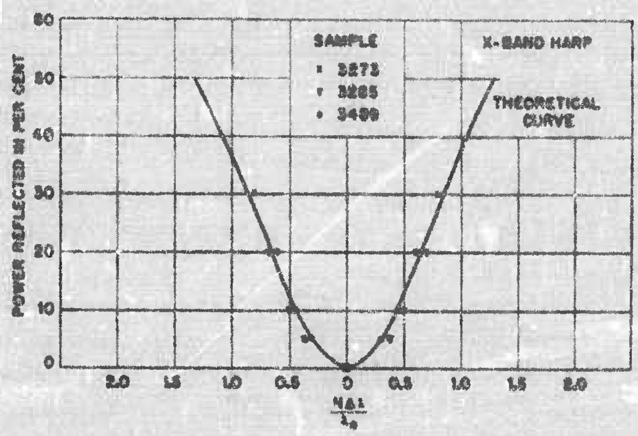

FIGURE 4. Comparison of theoretical and experimental absorption curves for X-band HARP.

closely. The S-band samples with the exception of sample No. 2027 also follow the theoretical curve.

It will be observed that in equation (72) the effect of μ_r can be described as an expression of the u axis. The contraction required to make the curve for sample No. 2027 coincide with the theoretical curve is approximately 2. Hence this sample has a permeability of approximately 2. The metallic component in this sample was molybdenum Permalloy.

In Figure 5 curves are shown for a series of samples made of the same pigment and same binder. The X- and S-band samples are identical except for thickness while the G-band (1.5 m) sample has a somewhat lowered pigment content in order to bring the layer closer to the critical loss. It will be noted that at 3 cm the permeability is unity. At 10 cm the permeability is slightly less than 2 as determined from the width of the resonance curve. This is accompanied by an

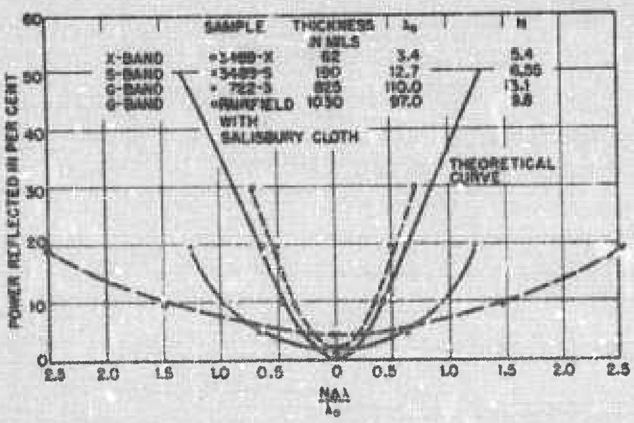

FIGURE 5. Comparison of magnetic HARP at widely different wavelengths.

increase in the refractive index. The G-band sample 722-3 has a permeability between 5 and 6 although the metallic concentration is lower. It is therefore clear that the metallic component which was a magnetic iron nickel alloy must have considerable permeability at 1.5 m which decreases with increasing frequency and reaches the value 1 between 3 and 10 cm.

The comparison of a quarter and a three-quarter wave layer has been made experimentally for quarter wave layers close to the critical loss. If the loss was greater than the matching loss it was found that the three-quarter wave layer had a standing wave ratio greater than 3, whereas, if the loss was less the standing wave ratio was less than 3 in agreement with the discussion in Section 11.1. The comparison has also been made by changing the wavelength instead of the film thickness by a factor 3. For nonmagnetic layers the three-quarter wave resonance point occurred at a wavelength three times as great to within 1 per cent. It follows that the real part of the dielectric constant varies by less than 2 per cent when the wavelength is changed by a factor 3. Indeed measurements of the dielectric constant of HARP materials at frequencies below a megacycle have given results substantially in agreement with microwave determinations. In magnetic materials the refractive index varies considerably because of the changes in permeability with wavelength discussed in the previous paragraph. The imaginary part of the dielectric constant also may change considerably with wavelength if the power factor of the binder is frequency-dependent or in a wavelength range for which the skin depth in the metallic component is approximately equal to the thickness of an individual flake. By proper choice of both factors materials have been formulated in which the imaginary component of the dielectric constant is also substantially independent of frequency over wide ranges.

For a few compositions, studies have been made of the temperature variations in ϵ_i and ϵ_r over a temperature range from −50 C to 70 C. For the lower temperatures there was no appreciable change in either ϵ_i or the resonant wavelength. For temperatures, however, above 60 C there was a substantial increase in ϵ_i while the resonant wavelength of the layer remained unchanged. Therefore, any expansion or contraction in thickness was compensated by a corresponding change in refractive index. The change in the loss perhaps arises from a temperature-sensitive power factor in one of the organic components in the binder.

The behavior of absorbing layers at different angles of incidence is shown in Figure 6. The power reflection coefficients there plotted are the minimum values obtained from the absorption curve at each angle of incidence. Sample 3287 is close to a perfect match at normal incidence while sample 3265 has a loss much below the critical loss. For a perfectly matched sample, according to equations (62), (63), the minimum standing wave ratio at an incident angle θ is $1/\cos\theta$. Thus for $\theta = 60°$, $x = 2$ and the corresponding power reflection coefficient is

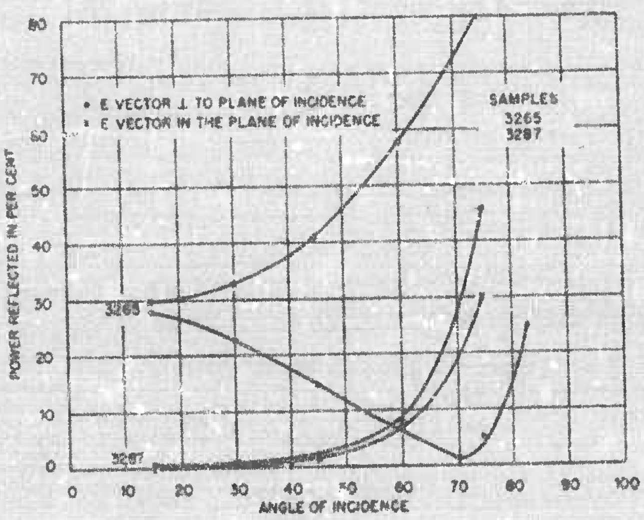

FIGURE 6. Minimum reflection coefficients for various angles of incidence and polarizations.

$[(2-1)/(2+1)]^2 = 0.11$ in approximate agreement with the experimental value shown in the figure. For a sample with less than the critical loss equation (67) may be used. From the figure $\theta_\perp = 70°$ so that $g = 0.34$. As this must be the reciprocal of the standing wave ratio for the minimum reflection at normal incidence, the reflected power at normal incidence is $(1-0.34)^2/(1+0.34)^2 = 0.26$. The experimental value shown in the figure is 29 per cent.

The resonant wavelengths for sample 3287 are given in Table 1.

TABLE 1. Resonant wavelengths for HARP sample 3287 for various angles of incidence and polarizations.

Angle of incidence (degrees)	⊥ Polarization (cm)	∥ Polarization (cm)
15	3.22	3.21
30	3.22	3.20
45	3.22	3.17
60	3.21	3.16

Because this sample had a refractive index of only 12 the minima were quite broad. Consequently the accuracy of the above values is not better than $\pm$ 0.01 cm. Nevertheless a definite shift to shorter wavelength is shown by the parallel polarization. From equation (44) k_z is smaller and therefore the wavelength in the layer is longer as θ increases. Hence to reach the resonance point the free-space wavelength must be reduced. Expansion of the second radical in equation (44) gives the fractional decrease in wavelength as $\sin^2 \theta/2\epsilon_2$. The shift in Table 2 indicates a longitudinal dielectric constant, ϵ_2, of the order of magnitude of 10.

When the angles of incidence are close to grazing incidence the arrangement described at the beginning of this section can no longer be used because the direct radiation from one horn into the other becomes too great and the geometrical conditions too poorly defined. Measurements at grazing angles have been made by using large parabolas separated a distance of 30 ft or more. The arrangement in principle is exactly as before but the coupling between antennas has been reduced and the geometrical definition of incident and reflected beam improved. A second method has sometimes been employed which shows directly how interference effects from reflections at grazing incidence may be eliminated with properly designed HARP. A horn with 2-in. by 6-in. aperture was mounted at the end of a metal plate 6 ft by 2 ft so that the center of its main lobe was directed parallel to the surface of the plate and parallel to its long side. The horn was excited with the electric vector parallel to the short dimension of the plate so the wave reflected from the metal plate was polarized perpendicular to the plane of incidence. The center of the horn was 6 in. above the metal plate. The arrangement is in effect the microwave version of Lloyd's mirror. The antenna pattern of the assembly was taken with and without a HARP covering on the plate. The HARP was designed to have low loss and hence to be effective at large angles of incidence. The antenna patterns are plotted in Figure 7. The deep and regularly spaced minima for the metal reflecting plate shows that the amplitude of the wave reflected from the plate is nearly equal to the radiation from the horn at each angle. The maxima and minima occur at the angles to be expected in this arrangement for a wavelength of 3.2 cm. The reduction of these maxima and minima shows the effec-

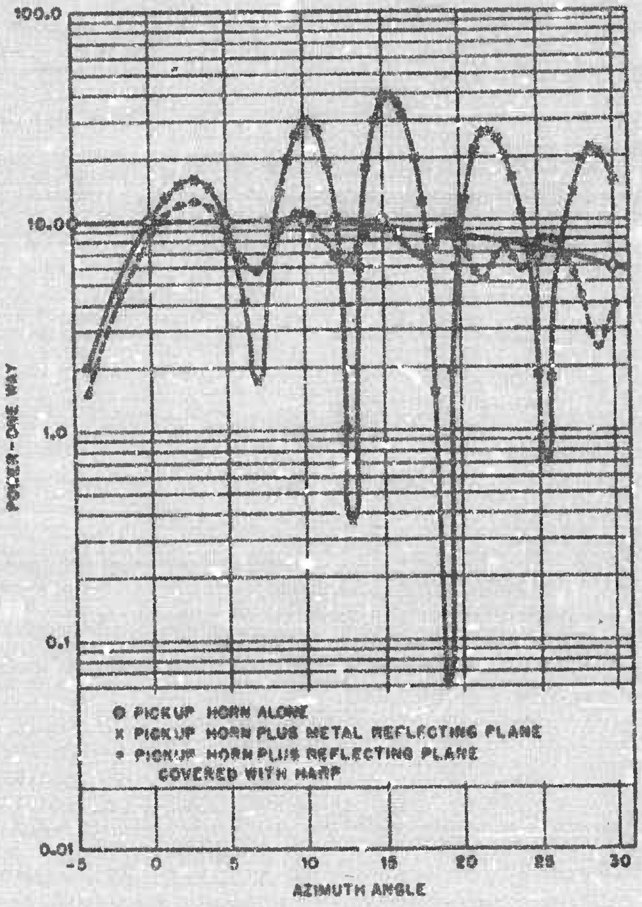

FIGURE 7. Effect of HARP at wide angles of incidence. (Lloyd's mirror).

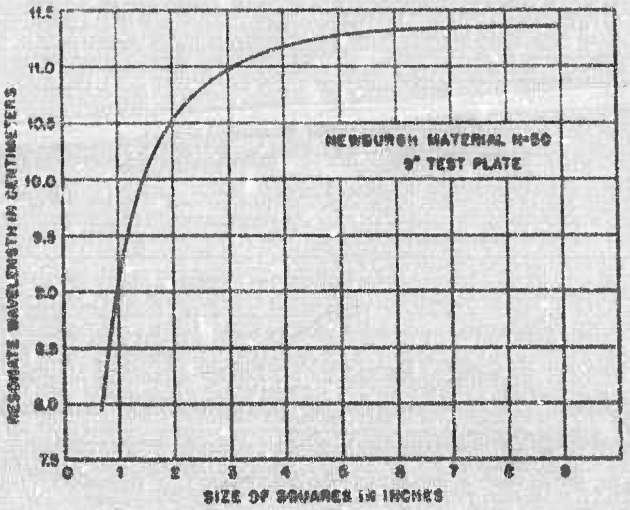

FIGURE 8. Resonant absorption wavelengths as a function of the sample size.

tiveness of HARP in reducing the reflection from the plate. The absorption is greatest at an angle of about 20° (angle of incidence = 70°). It may be noted that for angles less than 20° for which $g_\perp$ is greater than one, the phase of the wave reflected from the HARP layer is the same as for the metal plate. However, for angles greater than 20° for which $g_\perp$ is less than one, the phase of the wave reflected from the HARP layer is opposite to that reflected from the metal plate. This is clearly evident in the reversal of maximum and minimum at 25° and at 28°. It is entirely in accord with the discussion in Section 12.4.

In the measurement of these samples in a coaxial line the large effect of small air gaps between the sample and metal wall has been mentioned. A very similar phenomenon occurs if fine cuts are made across a HARP film. It is found as the spacing between the cuts is reduced the resonant wavelength shifts to shorter wavelengths corresponding to a smaller effective dielectric constant in the layer. That it is due to the small air gaps which the electric field traverses, is con-

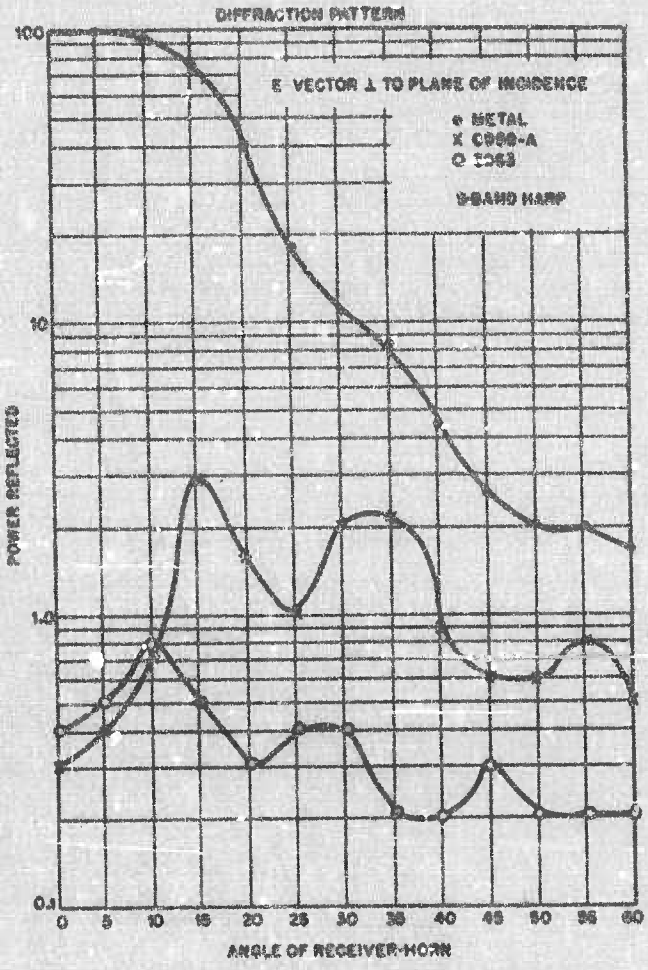

FIGURE 9. Comparison of the diffraction pattern about a HARP sample with that about a metal plate of the same size. (Perpendicular polarization.)

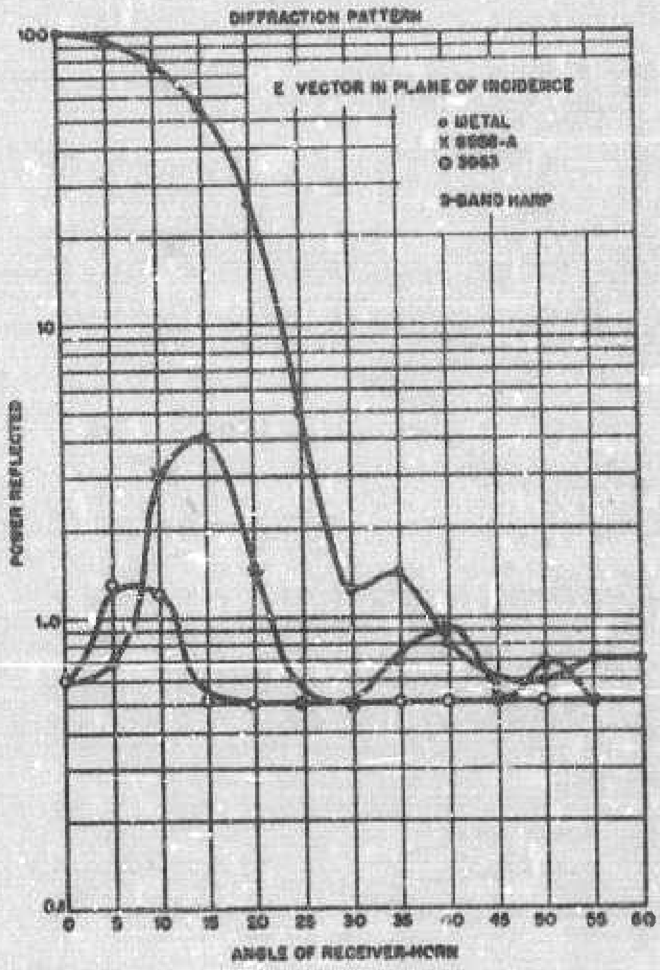

FIGURE 10. Comparison of the diffraction pattern about a HARP sample with that about a metal plate of the same size. (Parallel polarization.)

firmed when the cuts are made parallel to the electric vector of the incident wave. Thereupon they have a much reduced effect. In Figure 8 the shift in resonant wavelength is plotted for a series of samples ruled into squares of different sizes. It will be noted that when the squares become smaller than a wavelength on a side, the refractive index begins to drop very rapidly. It will also be observed that if a test plate is to give accurate results for the resonant wavelength of a layer, the dimensions parallel to the electric vector should exceed two waveleng s.

In all the previous discussions the effect of a HARP film on the specularly reflected radiation has alone been considered. Because reflecting objects are in general not large compared to a wavelength in the microwave region, it is of interest to study the diffracted radiation. If the diffraction pattern around a metal plate is examined experimentally, it is found that the secondary diffraction lobes are not altered in magnitude by covering the plate with high dielectric constant HARP. The only effect of the layer is to remove the principal diffraction lobe which in the limit of geometrical optics becomes the specularly reflected beam. However, if material of low refractive index and having some magnetic permeability is used, then some of the secondary lobes are also cut down in magnitude. Such experimental results are shown in Figures 9 and 10. The three diffraction curves shown in each figure are for the metal plate, the metal plate covered with sample G 958-A which had a dielectric constant of approximately 2,500 and the metal plate covered with sample 3963 which had a dielectric constant of approximately 30. These results indicate that it may be possible to formulate a material which substantially reduces certain parts of the diffracted radiation as well as that specularly reflected.

It has already been remarked that HARP material which is isotropic in the plane of the layer is required in most applications. The techniques for producing nondirectional films have been described in the previous chapter. In Figure 11 the absorption curves for a directional film formed by a succession of knifed layers are plotted. In this film the direction of the knife stroke was the same for each layer in contrast to the 90° rotation employed in fabricating nondirectional films. The curves show that the refractive index is 13 per cent greater when the electric vector is parallel to the direction of the knife stroke. In some films the difference in refractive indices has been as high as 20 per cent. Consequently films can be produced in which this difference is anywhere in the range from 0 to 20 per cent.

If a wave whose electric vector makes an angle ϕ with the directional axis is incident on a directional film, it may be regarded as the sum of two waves with the electric vector parallel and perpendicular to the axis. The relative amplitudes are $\cos\phi$ and $\sin\phi$ respectively. Each wave may be considered separately and the resultant obtained by vector addition of the two amplitudes. If the frequency of the incident radiation coincides with one of the resonance frequencies, that component will be absorbed and the other component alone will be reflected. The reflected wave will thus be linearly polarized perpendicular to the resonant axis. If a circular plate were covered with this material and were rotated about an axis perpendicular to the plate, the amplitude of the reflected wave would be 100 per cent mod-

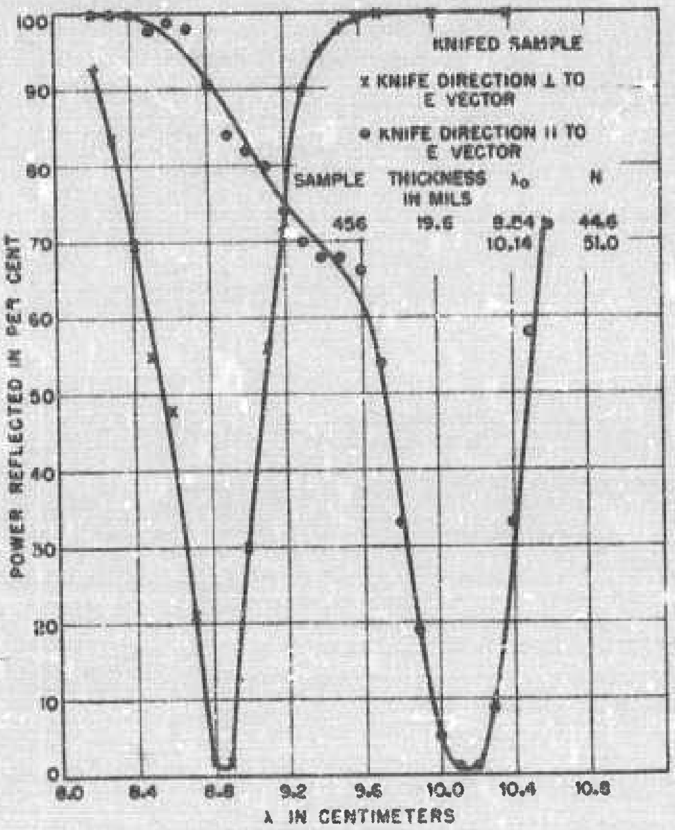

FIGURE 11. Resonant absorption of different incident polarizations for a directional HARP sample.

ulated with twice the frequency of rotation. The direction of polarization would go through a cycle making angles from $-90°$ to $90°$ and back to $-90°$ with the incident polarization direction, one cycle being made for each revolution. When the absorption of the sample is not complete, account must be taken of the phase changes near resonance. Since the component on the resonance axis may be shifted in phase by a large amount, the resultant reflected wave will be elliptically polarized. Thus directional HARP material may be used to produce a variety of polarization effects.

In some applications it is necessary to remove reflections from curved surfaces. The effects of curvature on a resonant layer are easily examined experimentally by studying the reflection from long cylinders of different radii. The results for two films, one of high and one of low refractive index, are shown in Table 2. The resonant wavelengths and minimum reflection coefficients for polarization of the incident electric vector parallel and perpendicular to the length of the cylinder are given. The values are obtained from complete absorption curves in which the reflections from the covered and metallic cylinders were compared at each wavelength.

TABLE 2. The effect of curvature on a resonant layer.

Newburgh Sample ($N = 50$)

Radius of curvature (inches)	Parallel polarization λ_0 (cm)	Parallel polarization Minimum reflection (per cent)	Perpendicular polarization λ_0 (cm)	Perpendicular polarization Minimum reflection (per cent)
∞	9.75	2	9.75	2
$1\frac{1}{2}$	9.6	2	9.4	6
1*	9.55	4	9.5	12
$\frac{1}{2}$	9.4	8	8.9	25

Sample 2036 ($N = 10$)

Radius of curvature	Parallel polarization λ_0	Parallel polarization Minimum reflection	Perpendicular polarization λ_0	Perpendicular polarization Minimum reflection
∞	10.7	4	10.7	4
1	10.8	7	10.6	6

*Absorption curves for this radius show some peculiarities probably because the diameter of the cylinder is exactly a half wavelength.

It will be noted that when the electric vector is parallel to the axis of the cylinder there is no appreciable change in the behavior of the absorber until the curvature is reduced to a small fraction of a wavelength. With perpendicular polarization an appreciable shift in resonant wavelength appears when the radius of the curvature is a half wavelength. For radii of curvature less than one-quarter of a wavelength there is a substantial increase in the minimum reflection. To compensate the difference for the two polarizations, directional HARP may be used with the direction of low refractive index parallel to the cylinder. The fabricating processes which give directional films have been previously discussed. The required directionality may also be achieved by a series of fine cuts into the layer which should be perpendicular to the axis of the material (cf. previous discussion). Whenever the thickness of the layer is unimportant, a film of sufficient band width that the shift in resonant wavelength is less than the band width may be used. It is probable that the minimum reflection coefficient for small radii of curvature could be improved by increasing the loss in the film.

11.2.1 Transmission Filters

The possibility of using a half-wave film of high dielectric constant material for a selective transmission filter has been mentioned in Section 9.1.1. In this section a detailed examination of the transmission and reflection characteristics of such filters is made. Their behavior in open space is first considered. The changes brought about when the films are used in a coaxial line or waveguide are then indicated.

Let $z = 0$ be the front surface and $z = -d$ be the back surface of the HARP film. If the incident wave is normal to the xy plane, the previous expressions for the electromagnetic field in the region $z \geq -d$ are valid. In particular, equations (3) and (4) still obtain. In the region $z \leq -d$ the field consists of a transmitted wave

$$\mathbf{E} = E_y = \beta e^{ik_0 z}, \tag{73}$$

$$\mathbf{H} = H_x = -\beta e^{ik_0 z}. \tag{74}$$

Correspondingly

$$\zeta(z) = -1, \; z \leq -d. \tag{75}$$

The continuity of $\zeta(z)$ at $z = 0$ and $z = -d$ requires that

$$\frac{1+\alpha}{1-\alpha} = -\zeta(0) = \gamma \frac{1+\alpha'}{1-\alpha'}, \tag{76}$$

$$\gamma \frac{1+\alpha' e^{2ikd}}{1-\alpha' e^{2ikd}} = -\zeta(-d) = 1 \cdot \tag{77}$$

The conditions for the continuity of the tangential electric field, which will also be needed, are

$$1+\alpha = A(1+\alpha'), \tag{78}$$

$$\beta e^{-ik d} = A\,(e^{-ikd} + \alpha' e^{ikd})\,. \tag{79}$$

The solution of equations (76-79) for the reflection and transmission coefficients, α and β, are

$$\alpha = (\gamma^2 - 1)\,\frac{e^{ikd} - e^{-ikd}}{(1+\gamma)^2 e^{ikd} - (1-\gamma)^2 e^{-ikd}}, \tag{80}$$

$$\beta = \frac{4\gamma e^{ik_0 d}}{(1+\gamma)^2 e^{ikd} - (1-\gamma)^2 e^{-ikd}} \cdot \tag{81}$$

A noteworthy result follows from these equations for a very thin film, $(kd)^2 \ll 1$. Equation (80) becomes

$$\alpha = \frac{i(\gamma^2 - 1)kd}{i(\gamma^2 + 1)kd + 2\gamma} \cdot \tag{82}$$

Here, as in the remainder of this section, $\gamma^2 \ll 1$ in all cases of interest. Expressing γ and k in terms of ϵ and μ

$$\alpha = \frac{-1}{1 - \dfrac{i\lambda_0}{\pi\epsilon d}}, \tag{83}$$

$$|\alpha|^2 = \frac{1}{\left(1 + \dfrac{\lambda_0 \epsilon_i}{\pi d\,|\epsilon|^2}\right)^2 + \left(\dfrac{\lambda_0 \epsilon_r}{\pi d\,|\epsilon|^2}\right)^2} \cdot \tag{84}$$

Hence, for very thin films the power reflection coefficient is proportional to $\epsilon^2 d^2$ rather than to ϵd^2. Consequently metal films much thinner than a skin depth will reflect a large portion of the incident energy. For example, at 10 cm the skin depth of Cu is about 10^{-4} cm. Nevertheless, a film 10^{-7} cm in thickness ($\epsilon = \epsilon_i = 3.4 \times 10^{-8}$) will reflect 80 per cent of the incident energy. Similarly a HARP film with $\epsilon_r = 2{,}000$ which is 1 mil thick will reflect 70 per cent of the incident energy.

In filters high selectivity and high transmission are desirable features. Hence, materials with small loss and as high refractive index as is consistent with a small loss are used. For these films $(k_i d)^2$ is always negligible in comparison with 1 and nonmagnetic materials are always used. Expressing k in terms of its real and imaginary parts and setting $\phi = \tan k_r d$, equations (80) and (81) can be written in this approximation as

$$\beta = -\frac{g + i\,\phi/2\gamma}{1 + g + i\,\phi/2\gamma}, \tag{85}$$

$$|\alpha|^2 = 1 - \frac{1+2g}{(1+g)^2 + (\phi/2\gamma)^2} \tag{86}$$

$$\beta = \frac{1}{\cos k_r d}\,\frac{1}{1 + g + i\phi/2\gamma} \tag{87}$$

$$|\beta|^2 = \frac{1}{\cos^2 k_r d}\,\frac{1}{(1+g)^2 + (\phi/2\gamma)^2} \cdot \tag{88}$$

The abbreviation $g = k_i d/2\gamma$ has been introduced. These equations show maximum transmission of $(1+g)^{-2}$ and minimum reflection of $g^2(1+g)^{-2}$. Both occur at $\phi = 0$. The quantity $2g(1+g)^{-2}$ is the energy dissipated in the film. The condition that $\phi = 0$ is

$$k_r d = n\pi \quad n = 1, 2, \cdots. \tag{89}$$

Thus the quantity g is

$$g = \frac{n\pi k_i}{2\gamma k_r} \cdot \tag{90}$$

Hence for a half wave filter, g is identical with the g for a quarter wave absorber of the same material. Refer to equations (13) and (15). It is interesting to note that material which is perfect for an absorber ($g = 1$), will transmit 25 per cent, reflect 25 per cent and absorb 50 per cent of the incident energy when it is used as a half-wave filter.

The wavelength dependence of the transmission is principally determined by ϕ, the term $1/\cos^2 k_r d$ changing only slightly over the region of transmission. If $\Delta\lambda$ is defined as in equation (21), then

$$\frac{\phi}{2\gamma} = \frac{1}{2\gamma}\tan\left[k_r d\left(1 - \frac{\Delta\lambda}{\lambda_0}\right)\right] = -\frac{n\pi\Delta\lambda}{2\gamma\lambda_0}$$

$$= -\frac{n\pi}{2}\,\frac{\Delta\lambda}{\lambda_0}\,\sqrt{\epsilon}\,. \tag{91}$$

For a half-wave filter, this is precisely the same quantity that governed the wavelength behavior

for a quarter wave absorber, equation (27). Equation (88) can now be written as

$$|\beta|^2 = \frac{1}{(1+g)^2}\,\frac{1}{1+\left[\dfrac{n\pi\Delta\lambda\sqrt{\epsilon}}{2\lambda_0(1+g)}\right]^2}. \tag{92}$$

The transmission as a function of wavelength is thus a typical resonance curve. The half width at the half-power point is

$$\frac{\Delta\lambda}{\lambda_0} = \frac{2(1+g)}{n\pi\sqrt{\epsilon}}. \tag{93}$$

Next suppose that the angle of incidence is θ and the electric vector is perpendicular to the plane of incidence. Equations (45-47) describe the field in the region $z \geq -d$ and equations (48, 49) remain valid. For the region $z \leq -d$ the equations for the field will be the same as in the region $z \geq 0$ except that x must be set equal to zero and all the field components must be multiplied by β.

$$\zeta(z) = \frac{1}{\cos\theta} \quad z \leq -d. \tag{94}$$

The continuity of $\zeta(z)$ at $z = 0$ and $z = -d$ requires

$$\frac{1}{\cos\theta}\,\frac{1+\alpha}{1-\alpha} = \frac{\mu_1 k_0}{k_z}\,\frac{1+\alpha'}{1-\alpha'}, \tag{95}$$

$$\frac{\mu_1 k_0}{k_z}\,\frac{1+\alpha' e^{2ik_zd}}{1-\alpha' e^{2ik_zd}} = \frac{1}{\cos\theta}. \tag{96}$$

The continuity of the tangential electric field gives

$$1+\alpha = A(1+\alpha'), \tag{97}$$

$$A\left(e^{-ik_zd} + \alpha' e^{ik_zd}\right) = \beta e^{ik_0 z\cos\theta}. \tag{98}$$

Comparison with equations (76-79) shows that the previous results apply provided that k is replaced by k_z of equation (43) and γ is replaced by $\gamma_\perp$ of equation (52). The first change has no effect because the difference between k_z and k is negligible. The second requires that γ and g be replaced by

$$\gamma_\perp = \gamma\cos\theta \tag{99}$$

$$g_\perp = \frac{\gamma}{\cos\theta}. \tag{100}$$

Hence, with increasing angles of incidence, the maximum transmission diminishes whereas the band width of the filter becomes smaller.

When the electric vector lies in the plane of incidence, equations (54) and (55) describe the field in the region $z \geq -d$ and equations (58) and (59) remain valid. For the region $z \leq -d$ the components of the field will be given by the same equations as in the region $z \geq 0$ except that x must be set equal to zero and each field component multiplied by β. Then

$$\zeta(z) = -\cos\theta \quad z \leq -d. \tag{101}$$

The continuity of $\zeta(z)$ at $z = 0$ and $z = -d$ requires

$$-\cos\theta\,\frac{1+\alpha}{1-\alpha} = -\frac{k_z}{\epsilon_1 k_0}\,\frac{1+\alpha'}{1-\alpha'}, \tag{102}$$

$$-\frac{k_z}{\epsilon_1 k_0}\,\frac{1+\alpha' e^{2ik_zd}}{1-\alpha' e^{2ik_zd}} = -\cos\theta. \tag{103}$$

The continuity of the tangential electric field gives equations (97) and (98). Comparison with equations (76-79) shows that the results for normal incidence also hold here if k is replaced by k_z of equation (44) and γ is replaced by $\gamma_\parallel$ of equation (60). The first change may now have some effect on the resonant wavelength but is otherwise negligible. The second gives in place of γ and g

$$\gamma_\parallel = \frac{\gamma}{\cos\theta}, \tag{104}$$

$$g_\parallel = g\cos\theta. \tag{105}$$

Hence, with increasing angles of incidence the maximum transmission improves while the band width of the filter becomes larger.

In Figure 12 the experimentally measured

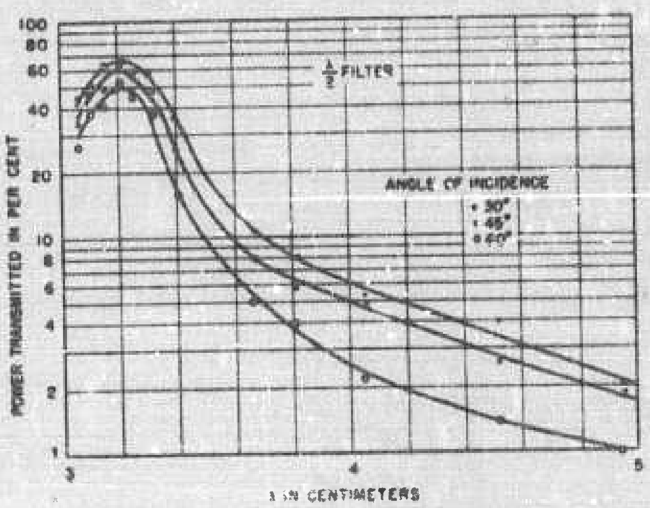

FIGURE 12. Transmission of a HARP filter as a function of wavelength for various angles of incidence.

transmission of a HARP filter is shown. The transmission was found by inserting a screen of the material two feet square between the transmitter and receiver antenna. These antennas are highly directive horns placed about six feet apart and pointing directly at each other. The ratio of received energy with and without the filter in place gave the power transmission coefficient. Care must be taken to avoid reflections from the filter into the transmitting horn by placing the screen at a sufficient angle with the line joining the horns. The presence of such reflections can be immediately recognized for the transmission of the screen then depends on its position between the horns. It was found that the angle of incidence on the screen could not be made less than 30° on this account.

The material of the filter had a refractive index of 13. As the maximum transmission is two-thirds at 30° incidence, $g = \sqrt{3/2} - 1 = 0.22$ and the theoretical half width according to equation (99) is $(2 \times 1.22)/(3.14 \times 13) = 0.060$. The experimental value of $\Delta\lambda/\lambda$ is $0.2/3.2 = 0.063$. The polarization used was perpendicular to the plane of incidence. Then at 60°, g should be 0.22 (cos 30°/cos 60°) = 0.38 and the corresponding maximum transmission is 52 per cent in good agreement with the experimental value shown in the figure. The decreased band width required by equation (99) is also quite evident at the larger angles of incidence.

The results obtained for normal incidence can be applied without change to a filter in a coaxial line just as in the case of an absorbing layer. Likewise the results for polarization perpendicular to the plane of incidence at angle of incidence given by equation (69) may be used to describe the behavior of a filter in the usual type of waveguide.

11.2.2 Composite Layers

Throughout the previous discussion it has been assumed that the absorbing medium is homogeneous. In this section the extension to inhomogeneous or composite layers is treated. A number of special problems which have arisen in the course of the development of HARP materials will be considered. These include the behavior of an absorber when a thin layer of low dielectric constant is inserted between the metal backing plate and the medium; the cross lamination of directional HARP to produce a nondirectional film; the behavior of a striated medium composed of alternate layers which are thin compared to the internal wavelength.

Suppose the medium consists of P layers separately designated by an index n which can have the values $0, 1, \cdots P$. The index 0 designates the air space which shall be to the right of the plane $z = 0$. Let the bounding plane between the nth and $n+1$ layer be $z = -l_n$. The thickness, d_n, of the nth layer is then given by

$$d_n = l_n - l_{n-1}. \tag{106}$$

The total thickness d of the medium is

$$d = \sum_1^P d_n. \tag{107}$$

The electric and magnetic fields in the nth layer are given in equations (1) and (2) if the subscript n is affixed to the quantities A, k, α', ϵ, and μ. The expression for $\zeta(z)$ is

$$\zeta_n(z) = -\sqrt{\frac{\mu_n}{\epsilon_n}}\,\frac{e^{ik_nz} + \alpha_n' e^{-ik_nz}}{e^{ik_nz} - \alpha_n' e^{-ik_nz}} \quad -l_n \le z \le -l_{n-1}. \tag{108}$$

The boundary conditions are that

$$\zeta_n(-l_{n-1}) = \zeta_{n-1}(-l_{n-1}) \quad n = 1, 2 \cdots P. \tag{109}$$

In this set of equations $\zeta_{P+1}(-l_P)$, the value of ζ at the metal reflector, has been defined to be zero. As the value of α_{n-1}' is fixed in terms of α_n' by equation (110), successive application of this recurrence relation will determine α_0' in terms of α_P'.

It is convenient to use a compact notation in equation (110). If γ_n is introduced in place of $\sqrt{\mu_n/\epsilon_n}$, it follows that

$$\zeta_n(-l_{n-1}) = -\gamma_n \frac{1 + \alpha_n e^{2ik_nd_n}}{1 - \alpha_n e^{2ik_nd_n}} \tag{110}$$

$$\zeta_n(-l_n) = -\gamma_n \frac{1 + \alpha_n}{1 - \alpha_n} \tag{111}$$

where

$$\alpha_n = \alpha_n' e^{2ik_nl_n}. \tag{112}$$

It will be observed that ζ is a linear fraction in α

of the type $a + b\alpha/c + d\alpha$. Let the operator T be defined as

$$T\alpha \equiv \frac{a + b\alpha}{c + d\alpha}. \tag{113}$$

It may be represented as a square array of the four coefficients a, b, c, and d. Thus

$$T = \begin{bmatrix} b & d \\ a & c \end{bmatrix}. \tag{114}$$

The first column contains the coefficients of the numerator and the second column contains the coefficients of the denominator. The first row contains the coefficients of α while the second line contains the terms independent of α. Since $T\alpha$ is a linear fraction, it is obvious that if each element in equation (114) is multiplied by a common factor, $T\alpha$ is unchanged. Likewise a common factor may be taken from the first column if $T\alpha$ is multiplied by this factor and a common factor can be taken from the second column if $T\alpha$ is divided by this factor. The advantage of using the above notation appears when a succession of two or more operations are considered. By definition, equation (113),

$$T_2(T_1\alpha) = \frac{a_2 + b_2\,(a_1 + b_1\alpha)/(c_1 + d_1\alpha)}{c_2 + d_2\,(a_1 + b_1\alpha)/(c_1 + d_1\alpha)}$$
$$= \frac{a_1b_2 + c_1a_2 + (b_1b_2 + d_1a_2)\alpha}{a_1d_2 + c_1c_2 + (b_1d_2 + d_1c_2)\alpha}. \tag{115}$$

If the coefficients of the fraction in equation (115) are compared with coefficients in the square array of the matrix product T_1T_2, they are found to be identical. Hence

$$T_2(T_1\alpha) = T_1T_2\alpha. \tag{116}$$

where T_1T_2 is the matrix product of T_1 and T_2.

Equations (110, 111) can now be rewritten as

$$\zeta_n(-l_{n-1}) = V_n\alpha_n. \tag{117}$$

$$\zeta_n(-l_n) = U_n\alpha_n. \tag{118}$$

where

$$V_n = \begin{bmatrix} \gamma_n e^{-2ik_nd_n} & -e^{-2ik_nd_n} \\ \gamma_n & 1 \end{bmatrix} \quad U_n = \begin{bmatrix} \gamma_n & -1 \\ \gamma_n & 1 \end{bmatrix}. \tag{119}$$

The reciprocal of U_n which will be needed later is

$$U_n^{-1} = \begin{bmatrix} 1 & 1 \\ -\gamma_n & \gamma_n \end{bmatrix} \tag{120}$$

for

$$U_n^{-1}U_n = \begin{bmatrix} 1 & 1 \\ -\gamma_n & \gamma_n \end{bmatrix}\begin{bmatrix} \gamma_n & -1 \\ \gamma_n & 1 \end{bmatrix}$$
$$= \begin{bmatrix} 2\gamma_n & 0 \\ 0 & 2\gamma_n \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

Equation (109) becomes

$$V_n\alpha_n = U_{n-1}\alpha_{n-1} \quad \text{or} \quad \alpha_{n-1} = V_nU_{n-1}^{-1}\,\alpha_n. \tag{121}$$

Let W_n be defined as

$$W_n = U_n^{-1}V_n = \begin{bmatrix} 1 & 1 \\ -\gamma_n & \gamma_n \end{bmatrix}\begin{bmatrix} \gamma_n e^{-2ik_nd_n} & -e^{-2ik_nd_n} \\ \gamma_n & 1 \end{bmatrix}$$
$$= \begin{bmatrix} 1 & \gamma_n^{-1}h_n \\ \gamma_nh_n & 1 \end{bmatrix} \tag{122}$$

where

$$h_n = \frac{e^{ik_nd_n} - e^{-ik_nd_n}}{e^{ik_nd_n} + e^{-ik_nd_n}} = \tanh ik_nd_n. \tag{123}$$

The solution of equation (121) for α_0 is therefore

$$\alpha_0 = V_PU_{P-1}^{-1}V_{P-1}\cdots U_n^{-1}V_n\cdots U_1^{-1}V_1U_0^{-1}\alpha_P$$
$$= U_PW_P\cdots W_n\cdots W_1U_0^{-1}\alpha_P. \tag{124}$$

From equation (109) with $n = P + 1$, it follows that $\alpha_P = -1$. Now

$$U_P\alpha_P = \begin{bmatrix} \gamma_P & -1 \\ \gamma_P & 1 \end{bmatrix}(-1) = 0. \tag{125}$$

Hence, equation (124) may be rewritten as

$$\alpha_0 = W_P\cdots W_n\cdots W_1U_0^{-1}(0). \tag{126}$$

Consider first the application of equation (126) to a homogeneous layer. Then

$$\alpha_0 = \begin{bmatrix} 1 & \gamma_1^{-1}h_1 \\ \gamma_1h_1 & 1 \end{bmatrix}\begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}(0) \tag{127}$$

$$= \begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}(\gamma_1h_1) = \frac{\gamma_1h_1 - 1}{\gamma_1h_1 + 1}. \tag{128}$$

Precisely the same result is obtained by solving equation (6) for α.

Next suppose the layer consists of two parts. Then

$$\alpha_0 = \begin{bmatrix} 1 & \gamma_2^{-1}h_2 \\ \gamma_2h_2 & 1 \end{bmatrix}\begin{bmatrix} 1 & \gamma_1^{-1}h_1 \\ \gamma_1h_1 & 1 \end{bmatrix}\begin{bmatrix} 1 & 1 \\ -1 & 1 \end{bmatrix}(0)$$
$$= \begin{bmatrix} 1 - \gamma_1^{-1}h_1 & 1 + \gamma_1^{-1}h_1 \\ \gamma_1h_1 - 1 & \gamma_1h_1 + 1 \end{bmatrix}(\gamma_2h_2) \tag{129}$$
$$= \frac{\gamma_1h_1 + \gamma_2h_2 - 1 - \gamma_1^{-1}\gamma_2h_1h_2}{\gamma_1h_1 + \gamma_2h_2 + 1 + \gamma_1^{-1}\gamma_2h_1h_2}. \tag{130}$$

If h_2' and k_2' are defined by the relation

$$h_2' = \tanh ik_2'd_2 = \frac{\gamma_2}{\gamma_1} h_2 , \tag{131}$$

equation (130) can be rewritten as

$$\alpha_0 = \frac{\gamma_1 \dfrac{h_1 + h_2'}{1 + h_1 h_2'} - 1}{1 + \gamma_1 \dfrac{h_1 + h_2'}{1 + h_1 h_2}} = \frac{\gamma_1 h - 1}{\gamma_1 h + 1} . \tag{132}$$

By virtue of the addition law for hyperbolic tangents

$$h = \tanh i(k_1 d_1 + k_2' d_2) . \tag{133}$$

In the first application of equation (133), suppose d_2 is sufficiently small that $(k_2 d_2)^2 \ll 1$.

Then

$$\frac{\gamma_2}{\gamma_1} h_2 = \sqrt{\frac{\mu_2 \epsilon_1}{\mu_1 \epsilon_2}}\, ik_2 d_2 = ik_0 d_2 \mu_2 \sqrt{\frac{\mu_1}{\epsilon_1}} = ik_1 d_2 \frac{\mu_2}{\mu_1} . \tag{134}$$

Hence

$$k_2' = k_1 \frac{\mu_2}{\mu_1} \tag{135}$$

and

$$h = \tanh\left[ik_1\left(d_1 + \frac{\mu_2}{\mu_1} d_2\right)\right] . \tag{136}$$

Equation (136) shows that with the interposition of a thin layer between HARP and the metal plate, the unit behaves as a homogeneous layer with a propagation constant $k_1[(d_1 + \mu_2 d_2/d_1)/(d + d_2)]$. For a nonmagnetic substance the thin layer therefore increases the thickness of the film just as though the added material had the same dielectric constant as the rest of layer. The following table shows the experimental results when adhesive layers of different thicknesses are placed between a HARP film and the metal backing plate. It will be observed that the resonant wavelength is proportional to the total film thickness. Consequently the effective propagation constant for the whole layer is unchanged as paper is added. The complete absorption curves show that the value of the minimum reflection is also unchanged as paper is added. In the application of HARP film to a metal backing plate this result must be kept in mind, for a thin layer of adhesive adds to the total thickness of the HARP film just as if it also had a high dielectric constant.

TABLE 3. Effect of adhesive layers of different thicknesses placed between a HARP film and the metal backing plate.

Thickness of adhesive in mils	Total film thickness, d, in mils	Wavelength λ_0 in cm	$\frac{\lambda_0}{4d}$
0.0	19.8	8.66	43.1
1.5	21.3	9.22	42.6
3.9	23.7	10.20	42.4
4.7	24.5	10.65	42.7

In the second application of equation (133) suppose the two materials have nearly identical electromagnetic properties. Let

$$\gamma_2 = \gamma_1 + \Delta\gamma = \gamma + \Delta\gamma , \tag{137}$$

$$k_2' = k_2 + \Delta k' = k + \Delta k + \Delta k' , \tag{138}$$

$$k_2 = k + \Delta k . \tag{139}$$

Equation (131) gives

$$\begin{aligned} h_2' &= \tanh ik_2 d_2 + i\Delta k' d_2 (1 - \tanh^2 ik_2 d_2) \\ &= \left(1 + \frac{\Delta\lambda}{\lambda}\right) \tanh ik_2 d_2 . \end{aligned} \tag{140}$$

Hence

$$i\Delta k' d_2 = \frac{\Delta\gamma}{2\gamma} \sinh 2ik_2 d_2 = \frac{\Delta\gamma}{2\gamma} i \sin 2kd_2 . \tag{141}$$

It has already been mentioned that certain processes for the production of HARP give directional materials. By laminating two layers at right angles it is possible to construct a nondirectional film. Let k_1, γ_1 refer to one axis and k_2, γ_2 refer to the perpendicular axis of the material. Equation (140) may be applied to determine the ratio of thickness required to effect this result. The imaginary parts of k and γ can be neglected. Then for one polarization of the incident wave

$$\arg h = k_1 d_2 + k_2' d_2 = kd + d_2\left(\Delta k + \frac{\Delta\gamma}{2\gamma d_2} \sin 2kd_2\right) . \tag{142}$$

In the other polarization the material constants k_1, γ_1 and k_2, γ_2 are interchanged. Hence

$$\arg h' = k_2 d_1 + k_1' d_2 = kd + d_1\left(\Delta k - \frac{\Delta\gamma}{2\gamma d_1} \sin 2kd_2\right) . \tag{143}$$

If the layer is to behave in the same way for both polarizations, arg h must be equal to arg h'.

Hence

$$\Delta k(d_1 - d_2) = \frac{\Delta\gamma}{\gamma}\sin 2kd_2. \tag{144}$$

Equation (144) will be applied to nonmagnetic HARP for which $\mu = 1$. Then

$$\frac{\Delta\gamma}{\gamma} = -\frac{1}{2}\frac{\Delta\epsilon}{\epsilon} \quad \text{and} \quad \frac{\Delta k}{k} = \frac{1}{2}\frac{\Delta\epsilon}{\epsilon}. \tag{145}$$

Equation (144) becomes

$$k(d_2 - d_1) = \sin 2kd_2. \tag{146}$$

Since the layer is supposed a quarter wave absorber

$$k(d_1 + d_2) = \frac{\pi}{2}. \tag{147}$$

The numerical solution of equations (146, 147) yields

$$kd_2 = 66^\circ \quad kd_1 = 24^\circ$$

$$\frac{d_1}{d_1 + d_2} = 0.27. \tag{148}$$

In the following table, the experimental results for films constructed of eight directional layers are shown. $\lambda_\parallel$ and $\lambda_\perp$ are the resonant absorption wavelengths for the two polarization states.

Then

$$W_n'' W_n' = \begin{bmatrix} 1 & i\mu_n'' k_0 d_n'' \\ i\epsilon_n'' k_0 d_n'' & 1 \end{bmatrix} \begin{bmatrix} 1 & i\mu_n' k_0 d_n' \\ i\epsilon_n' k_0 d_n' & 1 \end{bmatrix}$$

$$= \begin{bmatrix} 1 - \epsilon_n' \mu_n'' k_0^2 d_n'' d_n' & ik_0(\mu_n'' d_n'' + \mu_n' d_n') \\ ik_0(\epsilon_n'' d_n'' + \epsilon_n' d_n') & 1 - \epsilon_n'' \mu_n' k_0^2 d_n'' d_n' \end{bmatrix}. \tag{153}$$

If $\bar{\mu}_n$ and $\bar{\epsilon}_n$ are defined as

$$\bar{\mu}_n = \frac{\mu_n'' d_n'' + \mu_n' d_n'}{d_n' + d_n'}, \tag{154}$$

$$\bar{\epsilon}_n = \frac{\epsilon_n'' d_n'' + \epsilon_n' d_n'}{d_n' + d_n'} \tag{155}$$

equation (130) can be rewritten as

$$W_n'' W_n' = \begin{bmatrix} 1 & i\bar{\mu}_n k_0 d_n \\ i\bar{\epsilon}_n k_0 d_n & 1 \end{bmatrix} \tag{156}$$

where $d_n = d_n'' + d_n'$.

The corrections to the diagonal elements have been neglected as their effect can be shown to be small. Therefore the pair behaves as a single layer characterized by the constants $\bar{\epsilon}_n$ and $\bar{\mu}_n$ and having a thickness d_n.

TABLE 4. Resonant absorption wavelengths for nondirectional HARP

d_1 in mils	d_2 in mils	$d_1/(d_1+d_2)$	$\lambda_\parallel$ in cm	$\lambda_\perp$ in cm	$\lambda_\parallel - \lambda_\perp$ in cm
0	168	0.00	11.0	9.6	1.6
21	147	0.13	10.6	9.95	0.65
42	126	0.25	10.25	10.35	–0.1
63	105	0.38	10.1	10.75	–0.65

It will be noted that the resonant wavelengths for the two polarizations become equal at approximately the value of $d_1/(d_1 + d_2)$ predicted by equation (148).

The treatment of many layers which may be grouped in pairs and which are all thin will next be considered. Let ϵ_n', μ_n', d_n', k_n', γ_n' refer to one member of the nth pair while ϵ_n'', μ_n'', d_n'', k_n'' and γ_n'' refer to the other. Since $(k_n' d_n')^2$ and $(k_n'' d_n'')^2$ are small compared with unity

$$\gamma_n'' h_n'' = \sqrt{\frac{\mu_n''}{\epsilon_n''}}\, ik_n'' d_n'' = i\mu_n'' k_0 d_n'', \tag{149}$$

$$\gamma_n''^{-1} h_n'' = \sqrt{\frac{\epsilon_n''}{\mu_n''}}\, ik_n'' d_n'' = i\epsilon_n'' k_0 d_n'', \tag{150}$$

$$\gamma_n' h_n' = i\mu_n' k_0 d_n', \tag{151}$$

$$\gamma_n'^{-1} h_n = i\epsilon_n' k_0 d_n'. \tag{152}$$

The result may be applied to a medium constructed of alternate dielectric and conducting layers. It shows that each unit comprising a dielectric space and a conducting layer acts as though it had a conductance of $\sigma d'/d$ where σ is the conductivity of the conducting layer and d' is its thickness. An absorber based on the idea of gradually increasing conductivity as the layer is entered could therefore be made of regularly spaced sheets of increasing conductivity or of sheets with low conductivity spaced a decreasing distance apart.

Equation (156) may also be applied to an arrangement of alternately spaced high and low dielectric constant materials. If the dielectric constant of one of the substances is negligibly small, as is the case when thin HARP films are interleaved with paper, and if $\mu = 1$, the effec-

tive dielectric constant of a unit is simply $\epsilon(d'/d)$ where d' is the thickness of the HARP film and d the total thickness of the unit. If the unit is repetitive, $\epsilon(d'/d)$ is the effective dielectric constant of the medium. It will be noted that both the real and imaginary parts of ϵ are reduced in the same ratio. From equation (17) the standing wave ratio at the resonant point of the film is

$$x = g = \frac{\tanh k_i d}{\gamma} = \frac{\pi \epsilon_i}{4\sqrt{\epsilon}}. \tag{157}$$

Hence, if the HARP film has too high ϵ_i for a perfect match, $g > 1$, the interleaving of paper will lower the minimum reflection until a perfect match is reached because ϵ_i decreases more rapidly than $\sqrt{\epsilon}$. In fact if x_1 is the minimum standing wave ratio for the HARP film alone and x that for a diluted medium, then

$$\frac{x_1}{x} = \sqrt{\frac{d}{d_1}}. \tag{158}$$

Hence a perfect match should be reached when

$$\frac{d_1}{d} = \frac{1}{x_1^2}. \tag{159}$$

The following table shows the experimental results for thin HARP films interleaved with paper. The films had been prepared on thin sheets of paper so that no measurements were made on an undiluted HARP film.

It will be observed that $N\sqrt{d/d_1}$ is very nearly constant as should be the case if the propagation constant is proportional to $\sqrt{d_1/d}$. There are some irregularities in the standing wave ratio. If it is assumed that the last row of the table corresponds to a perfect match, the standing wave ratios, according to equation (158), should be $2.45/2.10 = 1.17$ for the third row, $2.45/1.82 = 1.35$ for the second row, and $2.45/1.47 = 1.68$ for the first row. The difficulty probably is the result of inaccuracies in the measurement of the standing wave ratios.

TABLE 5. Reflection from thin HARP films interleaved with paper.

No. of paper backed HARP samples	No. of added paper sheets between each sample	Total thickness in mils	HARP thickness in mils	$\sqrt{d/d_1}$	s.w.r.	Energy reflected (per cent)	$N = \lambda_0/4d$	$N\sqrt{d/d_1}$
13	0	82	38	1.47	2.62	20.	12.0	17.6
11	1	110	33	1.82	1.57	0.5	9.0	16.4
10	2	128	29	2.10	1.15	0.5	7.6	16.0
9	3	150	25	2.45	1.15	0.5	6.6	16.2

Chapter 12

TECHNICAL APPLICATIONS OF HARP

12.1 USES OF HARP

The high dielectric constants and permeabilities that are available in HARP materials open a number of new possibilities in the field of electronics. Not only are high dielectric constant and high permeability in themselves useful, but also there are probably associated properties which have not been investigated and which may lead to technical applications. The studies made to the present have been exclusively devoted to radar applications, largely in the microwave region. They are the subject of this chapter. Such applications are by no means representative of the possible uses for HARP.

Radar applications can be divided into two classes. The first class comprises systems which are primarily based on the properties of HARP. Two kinds will be discussed, namely, systems of radar camouflage using absorbent HARP layers, and identification systems based upon resonance and polarization characteristics of HARP films. These are the subjects of Sections 12.2 and 12.3. In the second class belong the many uses of HARP absorbers in improving the performance of radar systems and in making laboratory tests. They are the subjects of the remaining sections of this chapter. In Section 12.4 the removal of undesired reflections in specific radar installations is discussed. The possibilities of using HARP for screening and while tuning up a radar system are considered in Section 12.5. The concluding section deals with terminations and the laboratory uses of HARP.

12.2 CAMOUFLAGE

Of the many ways to confuse and interrupt enemy radar operation, the camouflage of a target by absorbent materials so that it becomes invisible is, in principle, the simplest and most effective means. Certain difficulties appear, however, when the factors governing the strength of the return radar echo are considered in detail.

A radar target in most cases can be characterized by a cross section σ which is defined as the ratio of energy per unit solid angle scattered backward to the incident flux of energy. It has the dimensions of length squared. It is determined by the nature of the target and, for targets large compared to a wavelength, varies rapidly as a function of the target orientation. The strength of a radar echo is proportional to the target cross section. It also depends on the intervening medium and on the characteristics of the radar set. For a given radar set the strength of the echo from an isolated target is proportional to the fourth power of the distance to the target. Hence for an isolated target the cross section must be reduced by a factor of $2^4 = 16$ if the maximum range at which the target can be detected is to be halved. For targets over smooth water, which is virtually a metallic reflector, the echo strength may vary as higher power of the distance because cancellation of the directly scattered radiation by the radiation reflected from the water takes place. At large distances, for surface search, the strength of the echo varies inversely as the eighth power of the target distance. In such a case the reduction of the cross section required to halve the range is a factor $2^8 = 256$. Therefore, very large reductions in cross section are necessary to change the radar visibility of a target by a significant amount.

Except in rare instances a target is a large and complex structure. The incident radiation is returned from many points with irregularly related phases. The various small parts of the target become important when cross section reductions of the above amount are contemplated. The task of screening or covering such parts on a ship, for example, is prohibitively difficult. In general, successful camouflage can only be expected when the target has a relatively simple and regular shape. A serious attempt to camouflage a ship would require a completely altered superstructure which would interfere with the proper functions of the ship, excepting possibly certain small vessels.

HARP absorbers so far developed as well as all other absorbers based upon destructive interference are inherently wavelength-sensitive. The present broadest band HARP film affords significant protection over a band about 25 per cent in width and simultaneously over another narrower band at one-third the wavelength. Consequently, they are useful only when the enemy radar which is used against a particular target lies within these bands. It is obviously necessary to forecast the nature of enemy radar at the time and place the camouflaged target will be employed.

An example of camouflage will illustrate these factors. In the closing months of World War II German U-boats were equipped with Schnorkel "breathing tubes" which enabled the U-boat to remain submerged for long periods of time. The exposed part of the Schnorkel was a relatively simple rounded shape which projected less than ten feet above the surface. Its detection at night was only possible with airborne microwave radar. The Schnorkel was covered with absorbent material[a] which was effective against the microwave airborne radar used by the Allies. The latter sets had been designed and produced only for bands at 9.1 cm and at 3.2 cm so that a single absorbing layer was effective against both bands. The uncovered Schnorkel was in itself sufficiently difficult to detect and the camouflage made it impossible to locate with the existing equipment. It will be noted that, for this target, a reduction in maximum range by a factor 2 against airborne search was really important, that the target was relatively simple in shape, and the limited wavelength range for which the camouflage was effective could be chosen to cover all types of existing airborne microwave radar operated by the Allies.

The return radiation from a simple target can be considered as specularly reflected if the target presents a surface normal to the incident direction which has a radius of curvature greater than a half wavelength. The corresponding cross section will be designated by σ_s. If the return radiation is due to the secondary maxima in the diffraction pattern of a large surface or if the surfaces normal to the incident direction have radii of curvature less than a half wavelength, it will be considered as diffracted radiation. The corresponding cross section will be designated by σ_d. In complex targets, the scattered radiation originates from the various scattering points in the target and will generally be composed of both diffracted and specularly reflected waves. In terms of σ_s and σ_d the total cross section is given by

$$\sigma = \sigma_s + \sigma_d + 2\sqrt{\sigma_s \sigma_d}\cos\phi\,. \tag{1}$$

where ϕ is the phase difference between the resultant specularly reflected wave and the resultant diffracted wave. If specular reflection is present at all, σ_s is usually considerably larger than σ_d.

HARP absorbers behave quite differently for specularly reflected and for diffracted radiation. With narrow-band HARP, the specular reflection is much reduced while the diffraction is unchanged in magnitude. The removal of the principal diffraction maximum (specular reflection) and the slight change in the secondary maxima (diffraction) were shown in Figure 9, Section 11.2. Hence, the application of narrow-band HARP to a target will only be effective if the cross section is mainly specular. A large scale test on a model submarine hull 100 ft long made at Fisher's Island[32] illustrated this behavior very clearly. The strength of the return echo was measured, with the target at a fixed range, as a function of orientation. The uncovered target gave a strong maximum, about 12 to 15 db above the signal for other orientations, when the target was beam-on. It was clearly due to the large and relatively flat surfaces which were then normal to the incident direction. When the surface was covered with a HARP absorber whose refractive index was about 30, the return signal was approximately the same in all orientations. The beam-on maximum had been reduced to the level of the scattering for the other orientations.

In a second test conducted by the Navy[33,34] at the Patuxent River Naval Air Station the effectiveness of HARP in reducing σ_s was also demonstrated. The target was a metallic right cylinder, 6 ft high and 6 ft in diameter,

[a] The "Wesch" absorber.[1] It consisted of 20% synthetic rubber impregnated with 80% carbonyl iron. Its electromagnetic properties were similar to sample 2027, Figure 2, Section 11.2, measured values of ϵ_r and μ_r being 3 and 7, respectively. Much higher metal concentration than that in HARP was necessary because the iron particles were spheroidal rather than flakelike in shape.

mounted on a raft. As the sides of the cylinder were perpendicular to the water, the radiation specularly reflected from the cylinder was again reflected from the water directly back on the incident direction. Therefore in smooth water the return radiation was specularly reflected and the cross section of the cylinder approximately the same as though it were viewed on a line perpendicular to its axis. The maximum range at which this target could be detected by airborne radar on the S and X band was determined for different altitudes of flight. The determinations were repeated when the cylinder was covered with the appropriate HARP. The S-band film had a refractive index of 30 while that for the X band had an index of 17. It was found in all cases that the maximum range had been reduced by a factor of two or more.

While HARP with high refractive index has little effect on the diffracted radiation this is not the case for broad-band magnetic HARP. The secondary maxima in the diffraction pattern which are not too far removed from the principal maximum may also be reduced (Figures 9, 10, Section 11.2). Likewise, the principal maximum is still removed when the surface has a small radius of curvature (see Table 3b, Section 11.2). It is, therefore, possible with this material to diminish σ_d. This possibility has not been exploited.

12.3 IDENTIFICATION

Several possibilities of using HARP to identify a radar target have been considered. Each involves an arrangement on the target which causes periodic variations in the strength of the radar echo. This audio-frequency modulation may be detected by a suitable modification of the receiver and the additional information thereby obtained may be used as a basis for identification. For airplane targets the rotation of the propeller periodically alters the target cross section enough to modulate the return signal. By applying HARP to the propeller blades it is possible to produce new subharmonic frequencies in the modulation the presence of which serve to identify the target. This system is commonly called Sambo. For other targets the modulation must be introduced by a rotating reflector. HARP is used to insure that the modulation is only present when the radar signal lies within a certain band of wavelengths. This system is called Harpoon. The presence of modulation at some wavelengths and absence at others is very difficult to simulate without HARP material. In addition the fact that the modulation is only present in a band of wavelengths diminishes the chance of its discovery by the enemy.

A receiver for detecting modulation has been discussed by Lawson.[35] There are essentially two parts, a pulse lengthening circuit (box-car generator) which maintains the peak value of the signal in the gate from one pulse to the next and an audio-frequency spectrum analyzer which employs an audio-frequency amplifier to drive a set of tuned reeds. Unfortunately separate audio-frequency channels with independent automatic gain controls were customarily used so that very little of the data has been analyzed quantitatively for the actual percentage modulation of the various frequency components. As a fixed modulation frequency is used in Harpoon, the amplifier and reeds can be replaced by a narrow band-pass amplifier. An ingenious type of analyzer for Sambo has been developed by Dunnington[36] which indicates directly the ratio of the percentage modulation of a subharmonic frequency to the percentage modulation of the normal fundamental frequency.

A useful criterion for the degree of modulation is the ratio of the desired signal intensity to the intensity from other causes at the same modulation frequency. It is termed the signal-to-noise ratio. Analysis shows that noise arising from the receiver as well as from neighboring pulse transmitters operating on the same wavelength may be minimized by using as narrow a gate as possible to reduce interference and by using a high repetition rate to reduce the effect of beats between the high harmonics of the signal modulation and the repetition frequency. The normal receiver noise is only important for very weak signals. The remaining source of noise is the target itself since fluctuations in its cross section are reproduced in the output of the pulse lengthening circuit. For example, if two airplanes are in the gate at the same time, the noise level becomes high because the phase of the signal from one plane changes very rapidly

with respect to that from the other (doppler effect). Also if the orientation of a large target is rapidly changed, a higher noise level appears for a similar reason. A study of the frequency distribution of such noise is necessary in the proper design of a Harpoon system for the identification of ships.

The noise level essentially determines the time, t, required for the indication of modulation. The frequency band containing the modulation signal is approximately $2/t$. If the modulation is sufficiently strong to give a signal recognizable above the noise in this band, then the indication is possible in the time t. As t is increased, an improved signal-to-noise ratio results until the band width has been narrowed to the inherent frequency stability of the modulation source. In practice band widths of a few cycles have been found necessary. The time t is therefore of the order of one second. As scanning systems are not "on target" this long the indication of modulation is generally confined to tracking systems.

A new physical principle, introduced by one of the authors,[b] which is unrelated to HARP, is the basis for Sambo. This is the generation of subharmonic frequencies in the propeller modulation by removing the symmetry of the propeller. Normally the blades of a propeller, in general n in number, are identical so that the configuration of the plane and propeller is exactly repeated when the propeller rotates through an angle of $360°/n$. Hence if ν_0 is the frequency of the shaft rotation, the lowest frequency appearing in the modulation is $n\nu_0$. If now the blades of the propeller are made electrically dissimilar, the frequency ν_0 appears in the modulation, as well as its harmonics. This result can be obtained by coating one of the blades with HARP. For the resonant wavelength this blade is no longer equivalent to the others. In practice all the blades are covered to preserve the mechanical balance of the propeller, and the dissimilarity achieved by painting one or more of the blades with a conducting silver paint.

The reliability of Sambo in discriminating between friend and foe depends upon the absence of a subharmonic frequency in an untreated plane. A large number of observations have been made by various agents with conflicting results. Lawson and his collaborators found these frequencies, called pseudo-Sambo frequencies, in many instances. They were but rarely seen with the equipment operated by Group 45. With a special installation at Brigantine, New Jersey, designed by MIT-RL for the purpose, pseudo-Sambo frequencies were never seen although hundreds of F6F targets were examined and the propeller modulation appeared normal in all respects. Likewise in many contacts made with the Dunnington receiver, pseudo-Sambo modulation never exceeded 5 per cent of the normal propeller modulation. It is probable that while pseudo-Sambo effects are present, they are of negligible importance and do not appear unless the system is operated in a way to detect very small percentage modulation.

The reliability of Sambo in providing positive identification depends upon the consistent presence of propeller modulation. The greatest part of the modulation is probably due to reflections from the flat or slightly rounded surfaces of the propeller blades. Hence strong modulation is usually present for a cone of angles about 30° in the forward direction. For Sambo the performance can be much improved by a spinner over the hub of the propeller. When one half of the spinner is covered with HARP (actually the whole spinner is covered and one half painted with conducting paint), a strong Sambo signal is present in a much larger cone, 80°, around the forward direction. In fact with the spinner treated it is no longer necessary to cover the propeller blades, thereby avoiding the difficult problem of permanently adhering HARP to the blades. The spinner provides better modulation because the reflection from it does not fluctuate violently for small changes in angle as is the case for the reflection from the surface of a propeller blade. This stability more than compensates for the smaller reflecting surface of the spinner. It may also be noted that a spinner divided into four quadrants, of which the opposite pairs are alternately reflecting and absorbing will generate a modulation frequency $2\nu_0$, instead of ν_0. Hence if it is used with a three-bladed propeller, it provides a positive means of distinguishing Sambo from pseudo-

[b] O. Halpern.

Sambo as the latter always includes the frequency ν_0.

Work on Sambo has shown that it is a feasible system of identification. The fact that no electronic equipment is carried on the plane, eliminating failures from this source, is a great advantage. There is no corresponding disadvantage in that the methods of applying HARP have been developed to a point where the service life of a propeller treated on its camber face is probably as great as that of an untreated blade.[37,38] It is surprising and regrettable that the positive results obtained with Sambo have not led to a far more extensive trial than the system has yet received.

Harpoon at the present writing is undergoing a preliminary test for the identification of small ships from aircraft. An airborne radar system has been modified for this purpose and rotating corner reflectors (rottetes) have been constructed by Bell Telephone Laboratories. Rottetes using HARP absorbers to produce the modulation were not satisfactory because in their design it was necessary to use reflections at very large angles of incidence. Against horizontal search, the rolling of the ship therefore interfered with their operation. The rottetes at present being tested use normal rotating corner reflectors which are enclosed in a radome covered with transmission HARP. The corner reflector is therefore only effective for the wavelength band which is transmitted by the HARP filters. To a large extent the success of these tests will depend on the skill with which the airborne radar has been modified to detect the modulation for it is clear that the major problem in an airborne set is that of keeping the radar trained on the target. It will be noted that this problem would be much simpler for a shipborne set and that this system is therefore much easier to develop for ship-to-ship identification.

In concluding this section, a scheme for identifying buoys or similar targets for navigational purposes may be mentioned. If such a target is covered with directional HARP, its cross section could be made small for one polarization of the incident wave and large for the other. The target, if examined by a radar set whose polarization could be varied, would then be distinguished by the relative strength of the return echo for various polarizations.

12.4 REFLECTIONS IN SPECIFIC RADAR INSTALLATIONS

The operation of radar systems is often impaired by reflections from structures near the antenna or from parts of the antenna support. Such reflections give rise to a variety of effects. Echoes resulting from illumination of the target by these reflections rather than the main beam may produce "ghosts" on the *plan position indicator* [PPI]. Reflections directly back into the antenna may disturb the operation of the transmitter. Interference between the reflected and the direct radiation from the antenna may seriously distort the antenna pattern of the system. Examples of each of these defects and its correction by HARP will be discussed.

The presence of side lobes in an antenna pattern is generally harmful for operation in a congested area. If, for example, a side lobe in the antenna pattern is 20 db down from the main beam, there is a 40-db discrimination in favor of the radar echo from a target illuminated by the main beam as compared to the echo from the same target illuminated by the side lobe. Nevertheless, a large and nearby object often gives a signal from side lobe illumination which is well above the noise level of the system and registers on the PPI, as a target. Since this signal appears when the relative bearing of the antenna with respect to the target is not zero but is equal to the angle between the main beam and the side lobe, it is properly termed a "ghost" or a "false target." It can readily be imagined that the presence of ghosts in an area containing many targets is a source of confusion in interpreting a PPI presentation.

When the main beam of the antenna illuminates any nearby structure, a portion of its energy is deflected into a different direction. Consequently, the antenna pattern of this installation will have additional side lobes at the angles corresponding to the directions in which energy has been deflected from the main beam. In general the interfering structure must intercept a considerable fraction of the energy in the main beam before side lobes of significant strength appear. Side lobes arise in the same way when a considerable fraction of the energy from the antenna feed illuminates supporting members of the reflector. These side lobes are

the source of ghosts which differ from ghosts from the normal side lobes in the feed and reflector itself only in that they do not appear at fixed angles with respect to the main beam but rather for certain bearings of the antenna with respect to its pedestal.

In the SG-1 installation aboard destroyers the antenna pedestal is located four feet behind the mast at a height where the mast is approximately 10 in. in diameter. When the antenna is pointed toward the bow of the ship, a section of the mast approximately 3 ft long is illuminated by the main beam. Engineers of the Raytheon Manufacturing Company made antenna pattern measurements on a mock-up of this installation. They found that for antenna bearings such that the mast was illuminated by the main beam, very broad side lobes appeared which were about 20 db down from the main beam. When the illuminated section of the mast was covered by a HARP absorber, appropriate for the SG wavelength, these side lobes were reduced by at least 10 db. To avoid possible effects of curvature in the reflecting surface (cf. Section 11.2), and to insure effective absorption over the SG scatter band, relatively broad band HARP was used. The antenna in these tests was a replacement design in which the side lobes had been reduced approximately 30 db. It is evident that the mast reflections must be reduced to the same level if the benefits of the replacement design in eliminating ghosts are to be realized.

Difficulties from illumination of the pedestal in the SK replacement antenna also made by Raytheon Manufacturing Company have been reduced by HARP. Only a few experimental samples of HARP have been made for a wavelength of 1.5 m. In tests made by Raytheon engineers one such sample placed over the illuminated part of the pedestal considerably reduced the side lobe in question. Work on this problem, which was in an early stage, was interrupted by the cessation of hostilities.

A slightly different difficulty was involved in the SO-5 antenna. Some of the energy from the antenna feed passed underneath the reflector, thereby giving side lobe in the antenna pattern in the backward direction. A baffle to intercept the radiation could only change the direction in which this side lobe appeared unless the radiation was absorbed instead of reflected. Tests made by Raytheon engineers resulted in a baffle covered with HARP appropriate for the SO-5 wavelength which reduced the side lobe to a point where it was no longer important. All production units of this equipment were supplied with this HARP covered baffle.

Reflections from neighboring structures may be the source of interfering signals in ground installations. In the GCA or "talk down" aircraft approach radar system (AN/MPN-1), the antenna is mounted on top of one end of a truck. At the other end a structure about ten feet high was a source of reflections for some positions of the antenna. A HARP screen for the appropriate wavelength placed in front of the structure was tested at MIT-RL by Group 104. Ground clutter caused by reflections was completely eliminated and the operation of the system markedly improved.

Reflections directly back into the antenna in general react on the transmitter and "pull" the magnetron off frequency. In the SCR-720 installation in the nose of P-61 aircraft the antenna rotates through 360°. Strong reflections directly into the antenna are present when the antenna is pointing backward at various metallic cylinders that house the radar equipment. The pulling was sufficient to upset the operation of the AFC circuits in this set. In tests made at MIT-RL, by Army personnel, it was shown that the difficulty was eliminated by placing a HARP covering over the metallic parts.

In some airborne navigation systems which employ a wide-angle beam, a smooth antenna pattern is necessary for the proper functioning of the system. If the pattern has large fluctuations in intensity, a uniformly bright target area appears on the scope crossed by a series of alternately bright and dark lines the contrast in which is determined by the fluctuations in the antenna pattern. In order that fluctuations should not seriously impair the mapping qualities it has been estimated that fluctuations in the antenna pattern should not exceed 3 db. It is clear that reflections from a surface in the neighborhood of an antenna can interfere with the direct radiation from the antenna to pro-

duce wide fluctuations of intensity in the resulting pattern (cf. Figure 7, Chapter 11).

Pattern measurements made by Group 54 of MIT-RL on a mock-up of the AN/APS-33 installation for P2 aircraft showed fluctuations of 16 to 20 db for different elevation angles. They occurred when the antenna was pointed toward the rear where a long tapered radome had been installed over the bomb bay doors. They were caused by interference between the direct radiation from the antenna and the radiation from multiple reflections between the radome and the surface of the bomb bay doors. Installation of HARP on the surface of the bomb bay doors reduced the fluctuations due to reflections to about 3 db. Incorporation of HARP in the radome installation of an AN/APS-33 on P2V aircraft has been recommended by Group 54 to the Naval Aircraft Factory, Philadelphia.

It should be expected that diffraction in the shadow region from a straight edge of an obstacle, which is due to the sharp boundary of the curve front, will not be effected by absorbent materials on either surface of the obstacle. Laboratory tests show that the presence of HARP on a screen does not affect the diffraction pattern in the shadow region. Hence, distortions in an antenna pattern from this source cannot be removed by HARP.

12.3 SCREENING AND TEST EQUIPMENT

For some purposes it is desirable to reduce the radiation from an antenna in certain directions. A metallic screen is seldom usable if the screen must be installed close to the antenna either because the reflection back into the antenna disturbs the transmitter or because the energy is again reflected by other parts of the installation into the original direction. HARP screening which avoids both difficulties has been successfully used for this purpose to reduce the altitude line in airborne radar and to reduce the cross coupling between neighboring antennas. Screening has similarly been used to prevent the escape of energy from the antenna of a system while it is being tuned up. Absorbing screens are also a necessary item of test equipment whenever a system must be tuned up in a space enclosed by metal. Examples of each of these uses will be discussed.

Nightfighter operations, particularly over water, have been much hampered by the presence of an altitude line on the radar scope. This line extends across the scope for all azimuths at a range equal to the altitude of the plane. It is caused by downward radiation from the antenna which gives a large signal despite the small amount of energy radiated downwards because the reflecting area under the plane is very large compared to a target. The first radar contact is usually made with a target well beyond the altitude line. Hence the target must be tracked through the altitude line as the distance is closed for attack. Contacts are frequently lost while the target is in the altitude line, especially if the enemy is taking evasive action.

The intensity of the altitude line may be estimated above smooth water. As the water is then a perfect mirror, the intensity of the return signal can be found from the image of the plane in the water. It is clear that, unlike a target echo, the altitude signal decreases with the square of the distance from the water. It is readily shown that the signal from a target whose cross section is σ and whose range r is equal to the altitude of the plane, becomes equal to the altitude signal when

$$p \cong \sqrt{\frac{\sigma}{r^2}} \tag{2}$$

where p is the ratio of intensity in the antenna pattern in the downward direction to the intensity in the main beam. For a cross section of 100 sq ft and an altitude of 1 mile $p = 1/500$ or the side lobe in the downward direction is about 26 db below the main beam. Hence, very good screening is necessary to reduce the altitude line to a harmless intensity for altitudes of 1 mile or less.

The British first recognized the possibility of eliminating the altitude line by HARP. In a series of tests with the AN/APS-4 installation on Firefly aircraft (carrier-based planes), very satisfactory results were obtained.[39,40] Subsequently the British placed a lend-lease order for 6,000 sq yd of X-band HARP to equip all Firefly aircraft of the fleet.

A series of tests on the AN/APS-6 installation in F6F aircraft was initiated by Lieutenant

Commander Orphanides at the Charleston, Rhode Island, Naval Air Station. It was found that the altitude line could be very much reduced by covering the bottom area of the radome with HARP and at the same time the operation of the radar was not impaired in any respect. Previous attempts to screen by metal foil had been unsuccesful. This series of tests was conducted on a number of planes by several experienced combat pilots. A pattern for covering the radome was established which gave adequate screening and at the same time left traces of the altitude line at the extreme azimuths which are useful in navigation. The Navy subsequently placed orders for X-band and S-band HARP with du Pont Company. A pilot plant at the Newburgh Division of the du Pont Company was put into operation and a total quantity of approximately 3,000 sq yd of HARP manufactured. The formulation studies and production process studies that preceded the actual production were made with the guidance of MIT-RL.[c]

Tests on the reduction of the altitude line have also been made in Army planes. At Boca Raton a squadron of B-26's had been equipped with SCR-720 radar for training Army nightfighters. The ground clutter near the altitude line was so severe that practice interceptions could not be made below an altitude of 8,000 ft. The bottom position of the radomes for the entire squadron were covered with HARP. The radar for interception purposes was operational for altitudes below 4,000 ft.

In systems employing separate transmitting and receiving antennas the coupling between the antennas is often a source of difficulty. The Radio Corporation of America [RCA] had an FM system of this type under development. It was necessary that the coupling be weak and at the same time constant. A screen covered with appropriate HARP was installed behind the antennas and tested by RCA engineers. It reduced the coupling due to the backward radiation of the parabolas and due to backward reflections from the surface of the radome to a point where the system was operational. At the same time sufficient isolation was provided that the coupling was independent of any changes produced by the movement of the operators behind the screens.

A similar problem was encountered by Group 71 of MIT-RL in the design of two beacon antennas mounted on the same rod. The transmitter was so closely coupled to the receiver that it regularly burned out the crystal of the latter. In tests by Group 71 it was found that the separation of the two antennas by a ring of the proper diameter covered with appropriate HARP reduced the coupling to a point where the difficulty was eliminated. These rings were installed on all production antennas made at The Gilfilan Bros., Incorporated.

The possibility of screening an antenna without disturbing the operation of a system led to an application of HARP in test equipment. It frequently is desirable in tuning up a radar system that no energy be radiated. In some jamming systems it is essential that there be no indication of its presence until the moment the jamming begins. Similarly for security reasons it is desirable to keep other systems off the air while they are being tuned up. Likewise in congested areas it is necessary to keep systems from radiating while these are being tuned up to avoid interference with other systems on the same wavelength. In all these cases a cap lined with appropriate HARP which fits over the antenna will prevent the radiation from escaping and at the same time the absorptive character of the material prevents any reaction on the system. The absence of reaction is essential in order that the system remain in tune when the cap is removed.

The caps made and tested by Group 71 of MIT-RL for the BUPX (AN/UPN-3, X-band beacon) antenna may be cited as an example. The caps were slightly larger than the radome over the antenna and were lined with X-band HARP. In one test the standing wave ratio in the line feeding the antenna was changed from 1.17 to 1.20 when the antenna was capped. This change is far below the tolerance set by tuning requirements. Preliminary tests made by the Aircraft Instrument Company on a similar cap for the Black Maria beacon, AN/APX-14, antenna indicate that a satisfactory solution to the problem will be found.

The problem of reaction on the radar system

[c] Under OSRD Contract OEMsr-1199.

also arises when a set is tuned in an enclosed space such as a hangar deck or a shop below deck. A folding wedge whose surface is covered with HARP has been designed and tested by the Naval Research Laboratory. It is placed directly in front of the antenna of the system under test. No measurable reaction is present when the antenna is pointed into the wedge. A small pickup horn is provided at the center of the wedge which may be used to excite an echo box or other test equipment. A much larger folding screen has been tested by Group 54 of MIT-RL for the same use with the Cadillac system (airborne early-warning radar) and was found to perform satisfactorily. It may be noted for the best results with narrow band HARP, the material for these wedges should be slightly differently designed than that for use at normal incidence inasmuch as the angle of incidence is about 45° with the electric vector in the plane of incidence (cf. Section 10.2).

12.6 TERMINATIONS AND LABORATORY USES

Terminations of HARP material are useful in equipment where space is at a premium. Their principal practical advantage lies in the reduced thickness compared with other types of terminations. However, they are suitable only for low and medium power levels and for relatively narrow bands.

The theory of quarter wave absorbers in a closed space has been discussed in the concluding portion of Section 11.2. In a coaxial line the layer should have the same dielectric constant, permeability and thickness as a layer used in free space at normal incidence. In a waveguide these constants should be the same as that for a layer in free space used at an angle of incidence θ, equation (69) Chapter 11, and with the electric vector polarized perpendicular to the plane of incidence. Materials fabricated in large sheets can therefore be tested without cutting the sheets by arranging the test equipment to satisfy these conditions.

The most difficult step in constructing terminations is that of cutting the sample to fit the waveguide or coaxial line. It has been found that the snugness of the fit against the metallic walls can cause quite large shifts in the resonant wavelength even when the material is attached to a metal foil. The latter precaution excludes the possibility of an air layer forming between HARP and the metallic backing. This effect has been insufficiently studied and is probably caused by air gaps between the material and the metal boundaries which the electric field must cross.

Only a few good coaxial terminations have been made. They were about ¼ in. thick for S band and had voltage standing wave ratios less than 1.1 at the resonant point. They were cut from broad band magnetic HARP suitable for normal incidence. A number of terminations were made and used to prevent resonance in the plungers of coaxial tuning stubs. As a power reflection coefficient of 10 per cent is entirely adequate for this purpose, no attempt was made to produce terminations with a very low standing wave ratio.

Considerably more effort was devoted to the problem of X-band waveguide terminations because they were an essential part of a directional coupler designed by Group 55 at MIT-RL. The thickness of 0.1 in. as compared to 1½ in. for other types of terminations was an important advantage in this case. The HARP films were adjusted for a 60° angle of incidence with the electric vector perpendicular to the plane of incidence. The angle given by equation (69) Chapter 11, was 45°. The larger angle yielded better results, probably because of the exact way the terminations, which were cut from a large sheet by a punch, fitted in the guide. It will be noted that material of substantially lower loss than normal incidence material was required.

Several hundred terminations were made and tested at 3.2 cm. Table 1 shows the wavelength dependence of a typical termination.

TABLE 1. The effect of wavelength on a typical HARP termination.*

λ in cm	Power standing wave ratio
3.13	1.15
3.20	1.10
3.26	1.07
3.30	1.10
3.35	1.15
3.40	1.22

*Sample 1449 in ½-in. by 1-in. waveguide with an approximate thickness of 90 mils.

A summary of the results for a number of terminations cut from the sample 3510-A-2 is given in Table 2. They were tested at 3.2 cm in ½-in. by 1-in. waveguide.

TABLE 2. The range of voltage standing wave ratios for a number of terminations cut from one HARP sample.

No. of samples	Range of power standing wave ratio
18	1.0 -1.1
8	1.1 -1.15
13	1.15-1.20
20	1.20-1.30
22	1.30-1.40
9	1.40-1.50
5	>1.50

HARP is often useful in the laboratory whenever high-frequency measurements in which there is leakage are undertaken. It may, for example, be used to cut down the leakage coupling between high-frequency components in a metal container. It may be used as a screen between high-frequency components in the same room. It is very useful whenever any kind of field measurements are made, particularly indoors. Disturbing reflections and scattering by parts of the room, by the operators or even by the probe itself, may be reduced. Likewise if the reflections or scattering from an object are being examined, the effect of the supports holding the object may be reduced. Whenever such measurements must be made indoors, a "dark room" lined with HARP makes accurate measurements possible. In order to secure the best possible results for this purpose the walls of the room should be cut up into wedges so that there are no large flat areas. As the material becomes more widely available, it should be a very useful adjunct to research and development in high-frequency laboratories.

GLOSSARY

AEW. Airborne early warning (Cadillac). AN/APS-20 plus other components. A 10-cm radar system to be used primarily as cover for naval task forces. Radar information from an airplane is relayed to the aircraft carrier.
AFC. Automatic frequency control.
AGC. Automatic gain control.
AGL. Airborne gunlaying. Any completely automatic airborne gunlaying system.
AGS. Airborne gunsight. A manually operated gun-pointing system, in which the operator tracks from a scope indication.
AI. Aircraft interception. A general designation for systems for detecting one aircraft from another.
AIA. A 3-cm AI system for carrier-based fighter aircraft.
AIBR. Acceleration integrator bomb release (refers to toss-bombing).
AIDED TRACKING. A combination of displacement tracking and rate tracking, that is, the operator has direct single-knob control of both the position and velocity of some reference line, such as the sight line or the gun line.
AMPLIDYNE. A d-c generator in which the response of the output voltage to changes in field excitation is very rapid; used extensively as part of a servo follow-up system.
AMTI. Airborne moving target indicator.
A-N BEAM. Radio beacon to guide aircraft.
AN/. Indicates joint Army-Navy designation for a system.
AN/APA-. Designates an attachment to an airborne radar system.
AN/APA-5. An auxiliary radar bombsight to be used with a search radar such as AN/APS-1, -15, -30, especially for low-altitude bombing.
AN/APA-16. Automatic low-altitude bombing attachment for search radars.
AN/APA-40 (40-A). Micro-H Mk II. A delay unit for use with AN/APS-15 or AN/APQ-13.
AN/APA-46. Nosmo. An attachment for bombing radars designed to provide synchronous tracking, using the Norden sight.
AN/APA-47. Visar. A system similar to AN/APA-46 (Nosmo) in which the visual bombardier performs the radar bombing also.
AN/APG-. Designates airborne radar ("pulsed") gunlaying or gun-sighting systems; also includes rocket-sighting systems.
AN/APG-1. A 10-cm AI and AGL system.
AN/APG-2. A 10-cm AI and AGL system.
AN/APG-3. A 3-cm gunlaying radar.
AN/APG-4. Sniffer. A 73-cm f-m system for automatic bomb-release at altitudes up to 400 ft.
AN/APG-5. A 12-cm ARO system.
AN/APG-8. Airborne radar similar to AN/APG-15 for installation in B-24.
AN/APG-13 (13A). Falcon. A 12-cm range-only radar for 75-mm cannon and rocket fire against water targets and isolated land targets.
AN/APG-13B. Vulture or Overland Falcon. A 10-cm range-only conical-scan radar for cannon or rocket fire against land targets.
AN/APG-14. Airborne radar similar to AN/APG-5 for installation in B-29.
AN/APG-15 (15A, 15B). A 12-cm conical-scan AGS system.
AN/APG-16. A 3-cm gunlaying radar, similar to AN/APG-3.
AN/APG-19. A 3-cm gunlaying system.
AN/APG-21. Terry, Pterodactyl, or Automatic Vulture. An automatic air-to-ground range-only radar, primarily for rocket fire.
AN/APN-1. A 68-cm f-m radio altimeter, usable up to 4,000 ft.
AN/APN-19A. Airborne respondor beacon.
AN/APQ-5. LAB. A low-altitude bombing system.
AN/APQ-7. Eagle. A 3-cm bombing radar.
AN/APQ-13. H2X. A 3-cm high-altitude bombing and navigation radar for use over land, similar to AN/APS-15.
AN/APQ-16. Airborne radar for precision bombing; consists of AN/APQ-7 plus the AN/APA-44 ground-position indicator.
AN/APS-. Designates an airborne search or interception radar system; frequently adapted for bombing.
AN/APS-2. ASG. A 9-cm ASV and search radar.
AN/APS-3. A 3-cm medium and low-altitude bombing radar for surface-vessel search and torpedo bombing.
AN/APS-4. ASH. A 3-cm ASV, AI and search radar for carrier-based aircraft.
AN/APS-6 (6A). A 3-cm search and interception radar, developed from AIA. Designed for carrier-based night fighters.
AN/APS-10. A 3-cm lightweight search and navigation system.
AN/APS-14. Relay link for transmitting radar information from airborne PPI to ground PPI.
AN/APS-15, 15A. H2X. A 3-cm high-altitude bombing and navigation radar for use over land.
AN/APS-16. A 57-cm tail-warning radar.
AN/APS-19. A 3-cm search and interception radar.
AN/APS-20. AEW or Cadillac. *See* AEW.
AN/APS-33. 3-cm airborne radar for search and low-altitude bombing when used with AN/APA-5.
AN/APX-14. Airborne identification equipment for use in conjunction with X-band radar.
AN/APX-15. Ella. Identification system (for B-29), depending upon propeller modulation.
AN/ART-22. A 100-cm airborne radar relay transmitter for Cadillac.
AN/ASG-10. A nonradar toss-bombing system.
AN/CPN-2. Ground beacon for precision navigation.
AN/CPN-6. An X-band ground respondor beacon.
AN/CPS-1. *See* MEW.
AN/CPS-4. A 10-cm ground medium-range air-transportable height-finding radar for use with separate search sets.
AN/CPS-5. A 23-cm ground early-warning and solid-search radar.
AN/CPS-6. V-Beam. S-band early warning and GCI ground radar system.
AN/MPG-1. A 3-cm mobile radar for fire control of coastal batteries against small vessels.
AN/MPN-1. A 10-cm search and 3-cm precision position-finding radar used in conjunction with radio communication to direct aircraft into landing approaches.
AN/PPN-1, 2. VHF responder beacons for paratroops.
AN/TPN-1. VHF transportable responder beacon.
AN/TPS-1. A 28-cm medium-range portable radar for general search.
AN/TPS-10. A 3-cm lightweight medium-range early-warning radar for air search and height-finding; Radiation Laboratory Little Abner.
AN/UPN-1, 2, 3, 4. Ultra-portable responder beacons.
ANGLE OF ATTACK. The angle (measured in the vertical plane through the axis of the fuselage) between the line of flight of an airplane and some fixed reference line in the airplane, such as the line determined by the leveling lugs, the boresight datum line or the zero-lift line. It varies with the speed, weight, and dive-angle.
ANGLE, DRIFT. The angle, in the horizontal plane, between the longitudinal axis of an airplane and its path relative to the ground.

ANGLE OFF. The angle between the line of flight of an airplane (usually a bomber) and the line joining it to an aerial target; sometimes measured from the nose, and sometimes from the tail.

ANTENNA. A conductor or system of conductors for radiating or receiving radio waves. A radar antenna includes the transmission-line feed or waveguide feed, the radiating elements proper, and the reflector.

ANTENNA, DRIVEN. An antenna which receives its power from the transmitter through the transmission line.

ANTENNA GAIN. A measure of the degree to which the radiation pattern is unidirectional; the ratio of the power per unit solid angle in the optimum direction to that from a source of equal power radiating isotropically.

ANTENNA, PARASITIC. An antenna which is not driven, but receives its current by induction from one or more other antennas.

ANTENNA PATTERN. The angular distribution of radiated power from the antenna assembly.

ANTENNA, YAGI. Consists of a reflector behind and a series of "directors," shorter than half a wavelength, which are placed in a row in front of a driven antenna. A narrow beam of radiation is produced, with the maximum radiation in the direction of the line of centers of the antennas (end-fire parasitic array).

AR. Aircraft rocket.

ARMA RESOLVER. A device used to perform vector addition of a-c voltages.

ARO. An airborne range-only radar system; includes S-band, X-band, and f-m systems.

ASB. A 60-cm Navy radar for surface search by carrier-based aircraft.

ASC. Navy designation for SCR-717B.

ASD, ASD-1. Early designation for AN/APS-3.

ASE. VHF airborne radar for surface search.

ASG. AN/APS-2.

ASH. AN/APS-4.

ASJ. Former Navy designation for AN/APS-17, a 12-cm tail-warning radar for use in bombers.

ASV. A radar system for detecting and homing on a surface vessel from the air.

ASVC. A 170-cm ASV system.

ATTENUATION. Attenuation of a wave is the decrease in amplitude with distance along a transmission line, in the direction of wave propagation, when the amplitude at any given place is constant in time.

ATTENUATOR. A device for controlling the amplitude of a signal. There are two types of r-f attenuators, cutoff (operating on the principle of a waveguide below cutoff), and dissipative (series resistance, or shunt conductance).

AUTOSYN. A synchro device like the selsyn (q.v.).

AVC. Automatic volume control.

BANDWIDTH. The difference between specified frequencies (in cycles per second) of a frequency band; usually these are the half-power points in the frequency spectrum.

BASE LINE. The horizontal or vertical line formed by the movement of the sweep on a cathode-ray tube with deflection-modulated presentation, for example, type A.

BBRL. British Branch Radiation Laboratory.

BEACON. An interrogated radar transmitter by means of which an aircraft can determine azimuth and range with respect to the location of the beacon.

BEAMWIDTH. The angle between the half-power intensities of the radiation of an antenna.

BEAVERTAIL. *See* AN/CPS-4.

BIAS. A potential difference between the electrodes of a vacuum tube; usually applied to that between cathode and a grid.

BIAS ERROR. A constant error as opposed to a random error.

BLACK MARIA. A radar system for the identification of friendly aircraft, designed to be used with AEW.

BLOCKING OSCILLATOR. An oscillating vacuum-tube circuit containing a vacuum tube and a transformer which produces pulses at a predetermined recurrence frequency. It may be free running or under control of a synchronizing voltage.

BOMB-RELEASE CIRCLE. For a given airspeed and altitude the locus of points at which a bombardier can release his bombs and hit the target providing he has the correct heading. This term is also applied to the electronic plot of such points on a radar scope.

B SCOPE. A type of indicator on which the signal appears as a bright spot, with azimuth angle as horizontal coordinate and range as vertical coordinate.

B′ SCOPE. Similar to B-scope, with elevation vertical and range horizontal.

BUPS. AN/UPN-1, -2.

BUPX. AN/UPN-3, -4.

BUTTERFLY. Radar for detection of moving vehicles by an aircraft.

c. Cycles per second. The symbol ∽ is also used for this term.

CADILLAC. *See* AEW.

CANCELLATION UNIT. A delay unit in which signals returned from nonmoving targets are canceled out.

CATHODE-RAY TUBE (CRT, OSCILLOSCOPE, SCOPE). A vacuum tube in which an electron beam is deflected by means of electric or magnetic fields. From the deflection, as observed on the face of the tube, the instantaneous values of the actuating voltages can be learned.

CENTRAL-STATION COMPUTER. An airborne gun-directing system which operates turrets by remote control.

CH. English long-wave early-warning radar used in a chain of stations along the coast.

CIT. California Institute of Technology.

CLAMP. To hold the base of a waveform or pulse to a given potential or current value.

CLUTTER. Radar signals from ground, sea, or other reflectors appearing in an oscilloscope indication, and interfering with observation of the desired target signals.

COHO. Coherent oscillator.

COINCIDENCE CIRCUIT. A circuit which transmits a pulse only when two or more input pulses coincide in time.

CONICAL SCAN. A system of scanning in which the axis of symmetry of the power beam describes a cone, usually of small angle. It is used when the angular position of a target must be known accurately.

CORNER REFLECTOR. A metallic or metal-coated structure resembling the corner of a cube, particularly effective in reflecting a radar beam.

COSECANT-SQUARED BEAM. A radar beam pattern designed to give uniform signal intensity for echoes received by airborne radars from distant and nearby objects. The beam intensity varies as the square of the cosecant of the elevation angle.

COUNTERMEASURES. Measures to combat enemy radar, such as jamming, window, anti-radar paint, Schnorkel.

CROSSOVER. The line about which the power beam from a conical-scan antenna revolves; also the relative power in the transmitted beam along that line in the antenna pattern.

CROSS TRAIL. *See* Volume 2, Figure 2, Chapter 6.

C SCOPE. Presentation in which the signal appears as a bright spot with azimuth as horizontal coordinate and elevation as vertical coordinate.

CW. Continuous wave.

CXAM. 150-cm shipboard aircraft-search radar.

CXEH. A Navy beacon similar to AN/CPN-6, an X-band ground respondor beacon.

CXBL. Laboratory prototype of SM.

CXHR. Experimental model of SX.

db. Decibel, a unit used to express a power ratio. The number of decibels equals ten times the logarithm to the base 10 of the ratio of the two powers: e.g., "3 db down" means a 50 per cent loss of power.

Decay Constant. The time required for a quantity to decay to $1/\epsilon$ of its original value. *See* time constant.

Delay. Refers to a delay in the passage of a current (or voltage) from one part of the circuit to another.

Delay Line. An artificial transmission line which produces as output a duplicate of what was given to it a definite short time before.

Detail Part. An element of an assembly, such as condenser, resistor, choke.

Director Sight. In this the gunner controls the line of sight. As he tracks, the computer positions the guns; *see* disturbed-reticle sight.

Dish. Antenna reflector.

Dipole (Antenna). Two metallic elements, each approximately a quarter wavelength long, which radiate the r-f energy fed to them by the transmission line.

Disturbed-Reticle Sight. A computing gunsight in which the gunner controls the gun line, and as he tracks the computer deflects the sight line from the gun line by the amount of the computed lead angle.

"Ditch." Abandon aircraft.

Doppler Shift. A shift in the frequency of a wave caused by the relative motion of the source and receiver.

Drift Angle. *See* angle, drift.

Driven Antenna. *See* antenna, driven.

Drone. A pilotless aircraft.

Duplexer. An assembly (containing a TR tube) which directs the received energy to the receiver and excludes the very much greater transmitted energy. This allows the same antenna and transmission line to be used for both sending and receiving.

Duty Cycle. Ratio of transmitter time-on to repetition period, for example a 1-μ pulse repeated every 500 μsec would have a duty cycle of 1/500. Duty ratio and duty are other terms for this. Duty factor is its reciprocal.

Eagle. AN/APQ-7.

Echo Box. A high Q resonant cavity which receives r-f energy through a pickup antenna during the transmitted pulse and reradiates this energy through the same antenna immediately after the pulse. The reradiated energy is picked up by the radar set. Since this energy from the echo box dies off exponentially, it will appear on an A-scope indicator as a flat-topped pulse, resulting from the saturation of the receiver by the high energy return, followed by an exponential curve. The time from the end of the transmitted pulse to the time that the echo box signal is lost in noise is called the "ringing time" of the echo box. The echo box may be used to test the overall r-f performance of the radar set, and if the echo-box pickup is in the antenna beam, the form of the antenna pattern can be shown graphically on the PPI.

Ella. AN/APX-15.

E Plane. The plane of the electric vector of a beam of radiated power.

Eureka. Respondor beacon.

Expanded Gain. The addition of a small portion of the indicator sweep voltage to the receiver gain voltage.

Exponential Smoothing. A function $x=x(t)$ is said to be exponentially smoothed when it is replaced by $y=y(t)$ defined by the differential equation $k\frac{dy}{dt}+y=x$; *see* Reference 58 in the Part IV bibliography of Division 14, Volume 2.

Falcon. AN/APG-13A.

Firefly. A modification of Butterfly giving a PPI presentation.

FM. Frequency modulation.

Frame Time. Time for a complete scan.

Frequency Pulling. A change in the frequency of a magnetron or other oscillator caused by a change in the load impedance.

Gain. A power ratio, usually referring to an amplifier.

Gain, Antenna. *See* antenna gain.

Gate. A square voltage pulse which switches a circuit on or off electronically.

GCA. Ground control of approach radar landing system; laboratory designation for AN/MPN-1.

GCI. Ground controlled interception.

GEE. A British navigation and bombing technique.

GEE-H. A beacon-bombing system based on GEE equipment.

GPI. Ground position indicator.

Ground Range. The distance from a point on the ground directly beneath an aircraft to a ground target, or ground radar.

GR-S/Clay 2/1. An organic polymer containing aluminum powder.

G Scope. A type of indicator presenting a spot with wings, which grow as the target approaches; azimuth is the horizontal, elevation, the vertical coordinate.

GTAP. Ground track aiming point.

Gun Fire Control System, Mark 56. Medium-range radar director for control of Navy 5-inch/38 cal. guns against aircraft.

Gun-Roll. A source of error in the computing of a lead by a gun sight arising from a neglect of one component of rotational motion.

Gyro Sight. A sight in which the angular rate is measured by a gyroscope.

HARP Material. Antiradar coating which absorbs microwave frequency radiation. Material with artificially constructed dielectric constant and loss.

Harpoon. A radar identification system in which a rotating corner reflector on a target ship is coated with HARP material producing modulation only when the radar signal is within a certain band of wavelengths.

H-Bombing. Bombing with the use of a navigational system in which the aircraft interrogates two ground beacons to determine its position.

Helipot. A helical potentiometer.

H Plane. The plane of the magnetic vector of a beam of energy.

H2S. S-band bombing and search radars.

H2X. X-band radars for bombing and search; includes AN/APS-15 and AN/APQ-13.

HF. High frequency; 3,000 to 30,000 kc.

HVAR. High velocity aircraft rocket.

I-F. Intermediate frequency. In microwave radar, the i-f amplifiers are usually centered at 15, 30, or 60 mc.

IFF. Identification as friend or foe. Radar systems which usually "interrogate" and receive a coded response if the target is friendly.

Impact Prediction. Computation of bomb-release point.

In-Out Switch. A switch for causing the range gates to unlock from a target signal and move to lesser or greater range.

Indicator. A device for displaying a received radar signal; usually a cathode-ray tube, although a dial or drum recorder may occasionally be meant.

Interrogator. A transmitting IFF radar set. Signals from it are received by a transpondor, and the latter replies

automatically, this reply in turn being received by the respondor.

INTERVALOMETER. A device for releasing a series of bombs at predetermined time intervals.

JINKING. Evasive motion of an aircraft in a series of straight line segments connected by curves.

J SCOPE. A modification of type A in which the time sweep produces a circular range scale near the circumference of the CRT face. The signal appears as a radial deflection.

K BAND. Refers to wavelengths around 1 cm.

KILLING DRIFT. Changing the heading of an airplane to compensate for wind, so that its ground track will pass through a given target.

LAB. Low-altitude bombing; AN/APA-5 and AN/APQ-5 are examples.

LEAD-COMPUTING SIGHT. A gunsight which computes the angle between the bore axis of the guns and the line of sight which is necessary to obtain hits.

LHTR. Lighthouse transmitter-receiver.

LIGHTHOUSE TUBE. A small oscillator tube, so called from its appearance.

LO. Local oscillator; a tube which produces a signal with a frequency near that of the transmitter. The LO signal is mixed with the echo to give a "beat" at intermediate frequency which is then amplified and detected.

LOBE-SWITCHING. Directing an r-f beam rapidly back and forth between two or more positions.

LOCAL TURRET. An airplane gun turret controlled by an operator located in it.

LONGWAVE. Refers to wavelengths greater than 1 meter, as opposed to microwave radar.

LORAN. A hyperbolic grid system of long range radio navigation, in which the navigator observes the difference in arrival times of pulses from two known stations.

L-SCOPE. A double A-scope presentation, for a double-lobe system. Deflections to the two sides of the time sweep indicate signals from upper and lower (or right and left) lobes.

MAD. Magnetic airborne detector for submarines under water.

MAGNETRON. A transmitter tube which produces the main pulse of ultra-high-frequency energy. The flow of electrons is controlled by an applied magnetic field instead of a grid.

MAJOR ASSEMBLY. A self-contained combination of subassemblies and detail parts, such as indicator unit, transmitter-receiver unit, power unit.

mc. Megacycles per second. One megacycle is a million cycles.

MC-627. Automatic plotting table for close-support bombing.

MARK 9, 10, 19, and 35. *See* radar equipment.

Mark 56. *See* gun fire control system, Mark 56.

MEW. Microwave early warning, a 10-cm ground radar for long-range detection or control of aircraft (AN/CPS-1); allows continuous plotting, in range and azimuth, of multiple targets.

MICRO-H. H-bombing with microwave radar systems.

MICROSECOND. 10^{-6} seconds.

MICROWAVE RADAR. Radar using wavelengths less than one meter.

MIL. Abbreviation for milliradian, an angle of one-thousandth of a radian; one degree is 17.45 milliradians.

MIL, ARTILLERY. An angle equal to 1/6400 of a circle; one degree is 17.78 artillery mils.

MILLIRADIAN. *See* mil.

MIT. Massachusetts Institute of Technology.

MODULATION. Varying the amplitude of the high-frequency signal according to a definite pattern.

MODULATOR. Also called a pulser. The part of the radar set which sends the high-voltage pulse to the transmitter. This pulse, in turn, starts the oscillation of the transmitter, which emits microwave radiation.

M-SCOPE. Modification of type A for range finding. The horizontal sweep is displaced vertically as in a step; the position of this step can be adjusted by some controlling device so that it coincides with the signal, at which point the device registers range.

MTI. Moving target indicator.

MULTIVIBRATOR. A form of relaxation oscillator, essentially a two-stage amplifier with feedback. It will oscillate of its own accord, or through an external synchronizing voltage.

MUSH. A vague descriptive term associated with the phenomenon of angle of attack of an airplane. An airborne fixed gun is said to "mush" when its bore axis is elevated above the line of flight.

MV. Multivibrator.

MX-344. A bombing computer.

NAB. Navigational Aid to Bombing, early designation for H2X radar.

NDRC. National Defense Research Committee.

NEOPRENE. Artificial rubber with carbon black in the ratio of 2 to 1.

NOISE. A random voltage appearing at the output terminals of a receiver with no impressed signal, if the amplifier has sufficient gain. On the A-scope noise appears as random spikes ("grass") on the sweep line. It is caused by random motions of electrons in the grid circuit of the first amplifier tube, to fluctuations in emission, shot noise at the plate, etc.

NOISE FIGURE. The figure of merit for sensitivity of a receiver. Defined as the ratio of the input power to kTB (where k is Boltzmann's constant, T the temperature in degrees Kelvin, and B the bandwidth in cycles per second) when the output signal power equals the output noise power. Noise figure is normally expressed in decibels (db).

NOSMEAGLE. Nosmo for Eagle.

NOSMO. AN/APA-46.

OBOE. A British bombing technique.

OFFSET BOMBING. Bombing in which the bombardier (visual or radar) sights on an aiming point different from the target.

OSRD. Office of Scientific Research and Development.

OWN-SPEED SIGHT. Same as vector sight.

PALMER SCAN. A type of antenna scan for searching.

PARASITIC ANTENNA. See antenna, parasitic.

PASS-BAND. Range of frequencies passed by a filter.

PB-OSRD. Pacific Branch, OSRD.

PDI. Pilot's direction indicator.

PGP. Pulse glide path experimental aircraft landing system.

PHANTASTRON. A precision delay circuit.

PLANE OF ACTION. The plane containing the line of motion of an aircraft and the target.

PLUMBING. Waveguide and coaxial cable or transmission line, with fittings.

POLYROD. Polystyrene plastic rod.

POSITION FIRING. A rule-of-thumb procedure for use by an aerial gunner whose gun is equipped with a ring and post sight. The lead taken depends only upon the relative bearing of the target.

PPI. Plan-position indicator. Scope indication with circular sweep, showing ground objects in approximately correct relationship as on a map.

PRESSURIZE. The filling of the r-f line with air at a pressure greater than atmospheric. Its purpose is twofold: (1) to prevent breakdown of the components at high altitudes and (2) to protect against transmission losses caused by materials in the atmosphere, such as dirt and water.

PRF. Pulse recurrence frequency.

PROBABLE ERROR. A magnitude associated with the measurement of a quantity such that half of the errors are less and half are greater than the given magnitude.

PROXIMITY FUSE. A fuse for shells, bombs, or rockets which

sends out radio waves and explodes at a predetermined distance from a target (VT fuse).

PULSE. Refers to the emission of power for a short time, followed by a period of no emission; one of the fundamental characteristics of most radar systems.

PULSED DOPPLER SHIFT or PRINCIPLE. See Division 14, Volume 2, Part V.

PULSE SHAPE. The graph of radiated energy as a function of time.

PURSUIT COURSE. A course in which a pursuer is continuously moving in the direction of the pursued; see Division 14, Volume 2, Section 21.1.1 for more complex modifications of this concept, such as lead pursuit, aerodynamic pursuit, and aerodynamic lead pursuit course.

Q (OF A RESONANT SYSTEM). The Q of a specific resonance mode of a system is 2π times the ratio of the energy stored to the energy lost per cycle, when the system is excited in this mode. A high Q circuit is lightly damped, has a small decrement, a sharp resonance peak, and a high selectivity. Q is a figure of merit.

RADAR. Abbreviation of "radio detection and ranging"; usually refers to systems using ultra-high-frequency waves, with the pulse technique.

RADAR EQUIPMENT, MARK 9. A 10-cm ship fire-control radar for AA batteries; used with Gun Director Mark 45; obsolete.

RADAR EQUIPMENT, MARK 10. A 10-cm ship fire-control radar for AA batteries; obsolete.

RADAR EQUIPMENT, MARK 35. A [illegible]n automatic-tracking radar, an integral part of the Gun Fire-Control System, Mark 56.

RADIATION LABORATORY. In this book this designation is reserved for the Massachusetts Institute of Technology Radiation Laboratory which carried on radar research and development from 1940 to 1945 under the direction of Division 14, NDRC.

RADOME. A general name for radar turrets which enclose antenna assemblies.

RANGE MARK. One of a series of spots or lines on a scope to indicate the range of target signals.

RANGE WIND. The component of the wind in the direction of the target.

RATE END. A component of the Norden sight.

RATE SIGHT. A gunsight in which the lead is computed from the rate of tracking of the target.

RC NETWORK. A circuit containing resistances and capacitances.

RC-294. Plotting board for SCR-584.

REBECCA-EUREKA. *See* Division 14, Volume 2, Section 10.4.2.

RECEIVER SENSITIVITY. Related to the ability of a receiver to detect weak signals. It is measured by the noise figure (q.v.) in the case of microwave radar.

REFLECTOR, CORNER. *See* corner reflector.

RESPONSOR. *See* interrogator.

r-f. Radio frequency. A general term for the frequency to be radiated, not confined to any specific limit.

r-f HEAD. A major assembly unit of a radar system which includes the magnetron, duplexer, part or all of the receiver, and occasionally other parts.

RHI. Range-height indicator.

RINGING CIRCUIT. A circuit in which the oscillations die out slowly, as when a bell is rung.

RINGING TIME. *See* echo box.

RL. Radiation Laboratory of the Massachusetts Institute of Technology.

ROTTETES. Rotating corner reflectors used in the Harpoon identification system.

SAMBO. A radar identification system in which HARP film is applied to the propeller blades of the target aircraft producing new subharmonic frequencies in the normal propeller modulation.

SAWTOOTH SWEEP. A sweep in which the motion of the electron beam is controlled by a sawtooth voltage wave, that is, the voltage rises slowly and linearly and then declines rapidly.

S-BAND. Refers to wavelengths of the order of 10 cm.

SCANNER. A device which directs the r-f beam successively over all points in a given space.

SCI. Ship-controlled interception. Similar to GCI.

SCOPE. Oscilloscope, cathode-ray tube. For the various types of scope presentations, see under the appropriate letters.

SCR. Signal Corps radio set.

SCR-520. A 10-cm airborne search and interception radar.

SCR-540. A 155-cm airborne radar for detection of other aircraft.

SCR-582A. An 11-cm fixed coastal-surveillance radar for use against ships and low-flying aircraft.

SCR-584. Mobile medium-range search and track radar, designed for antiaircraft fire control, and also applied to ground control of aircraft.

SCR-598. Prototype of AN/MPG-1, not mobile.

SCR-615A. 1-cm fixed medium-range radar for search, height-finding and GCI.

SCR-682A. A 1-cm long-range coastal search radar for detection of ships and low-flying aircraft.

SCR-695. A 160- to 191-cm transpondor.

SCR-702A, B. Former Army designations for AN/APG-2, and AN/APG-1, respectively.

SCR-717. An airborne radar system for detection of surface vessels.

SCR-718. A 68-cm pulsed altimeter for use up to 40,000 feet.

SCR-720. A 10-cm airborne search and interception radar, especially for nightfighters.

SCR-729. An IFF interrogator-responsor.

SECOND DETECTOR. The detector which converts i-f (30 or 60 mc) into video.

SECTOR SCAN. Motion of the scanner reflector back and forth through a limited angle, instead of through 360°.

SELSYN. A self-synchronous motor or generator (autosyn, synchro; the latter name has been chosen by the Services). A means of making a shaft rotate by the same amount as another shaft at some remote position.

SERVO SYSTEM. A mechanical, frequently electromechanical, system for transmitting accurate mechanical position from one point to another by electrical or other means. The position is corrected by feeding back an error signal.

SERVO-AMPLIFIER. The amplifier of power impulses in a servo system.

SERVO LOOP. That collection of elements in a servomechanism which measures the error in the quantity to be controlled and applies a correction tending to reduce that error to zero.

SG, SG-1. A 1-cm shipborne long-range surface-search radar for use on battleships, cruisers, and destroyers.

SHORAN. Short range navigational system, made up of two ground radars (AN/CPN-2) and one airborne set (AN/APN-3).

SIDE LOBE. A portion of the beam from a radar antenna other than the main lobe; usually much smaller.

SINEPOT. Sine potentiometer.

SK. A 150-cm shipborne long-range aircraft search radar for installation on battleships, carriers, and cruisers.

SKIATRON. Dark-trace cathode-ray tube used in projection plan-position indicators, Navy type VG.

SKID (of an airplane). Motion of an airplane in a direction different from that in which it is heading.

SKYWAVE. A radio wave reflected from the ionosphere; this occurs at frequencies less than 20 mc.

Slant Range. Range from an aircraft to a ground target or radar; distinguished from ground range.

SM. A 10.7-cm high-power radar for fighter direction and surface search on aircraft carriers.

Sniffer. AN/APG-4.

SO-5. 5-cm surface-search radar for installation in PT boats and landing craft.

SP. Lighter, simplified model of the SM radar.

Spinner. Rotating antenna assembly; a scanner.

SS Loran. Skywave synchronized Loran.

Stability (of a sighting system). Stability exists when, if the gun is given a small quick jerk in some direction, the reticle is jerked in the same direction.

Stabilize (as a scope, or line of sight). To maintain a system in a desired orientation, in spite of motion of aircraft or ship.

Stadiametric Ranging. Determination of range to an airplane target by bracketing the image between optical markers in the sight, which then computes the range by the principle of similar triangles.

Storage Tube. *See* Section 23.3.2b.

SU. 3-cm medium-weight, medium-power SSV radar for use on DE's and other small vessels.

Subassembly. A part of a unit assembly, replaceable as a whole, consisting of a combination of detail parts (q.v.), such as i-f amplifier section or voltage regulator.

Sweep. The beam of electrons passing from the electron gun to the face of the CRT makes a point of light on the face of the tube. By proper voltage or magnetic control this point of light can be made to move in any direction. By making this motion rapid and continuous, the point of light becomes a line of light, and is called a sweep.

Sweep Circuit or Generator. A circuit which produces at regular intervals an approximately linear or circular, or other form of movement (sweep) of the beam of the cathode-ray tube.

SX. Combined 10-cm high-power general-search radar and high-power fighter-direction radar for carriers.

Synchro. Same as selsyn, autosyn. This designation is preferred by the Services.

Synchronization (of a bomb-sight). Establishment of the proper rate of motion of the bombing computer index so that the index tracks the target.

Synchronization (of a gunlaying system). Establishment of the tracking of a target in range and angle, by the gunlaying system.

Terry. AN/APG-21.

Test Equipment. An assortment of instruments provided with a radar set to enable the maintenance man to determine accurately whether the set is performing properly in its various functions, and to aid in locating improperly operating components and in restoring them to proper condition.

Thermistor Bridge. A bridge with sensitive resistors whose resistance varies significantly with temperature.

Time Base. The sweep on an indicator tube begins at zero time, the instant that energy is transmitted, and ends at a later predetermined time. It may be called a time base. Since time and distance are proportional in the radiation of the energy from its source, the distance of any signal on the sweep from the beginning of the sweep may be translated into units of geographical distance. In some circuits, the beginning of the sweep is delayed for a fixed or variable time after the firing of the transmitter. It is then known as a delayed sweep.

Time Constant. The time required for a variable which obeys an exponential law to change by a fraction $1/e$ of the total change.

TR. Transmit-receive tube; a TR box or, preferably, switch, is the assembly containing the TR. *See* duplexer.

Trail. The vector giving the displacement of the actual point of impact of a projectile or bomb from the point where it would have hit if it had moved in a vacuum.

Trajectory Drop. The angle (in mils) between the line along which a projectile was fired and the line from the gun to the position of the projectile.

Transpondor. A radar system which receives and replies to an IFF interrogator (q.v.). Also a similar system used as a radar beacon for navigational purposes.

TRE. Telecommunications Research Establishment (British).

Trigger Pulse. A pulse which starts a cycle of operations.

Tuning. The process of adjusting circuits to resonance with the frequency of a desired signal.

UBS. Universal bomb sight.

UHF. Ultra-high frequency (200 to 3,000 mc).

V Beam. AN/CPS-6.

Vector (verb). To direct (an airplane) toward a moving target (military usage in aircraft interception).

Vector Sight. A gunsight which gives the lead as a constant times the sine of the angle off. The constant depends upon the own speed of the aircraft, altitude, and ammunition.

VHF. Very high frequency (30 to 300 mc).

Video. Electrical form in which a returned radar echo is transmitted to the indicator to be made visible.

Visar. AN/APA-47.

Vulture. AN/APG-13B.

Waveguide. A hollow pipe, usually of rectangular form, used as an r-f transmission line. The limits on the dimensions of the pipe are determined by the wavelength to be transmitted by the pipe, also by the shape of the pipe and the mode of transmission. There are other types of waveguides, such as solid dielectric cables through which it is possible to transmit energy. Waveguides may be straight, twisted, curved, tapered, or flexible.

Window, Chaff. Radar countermeasure, consisting of strips of metal foil or metal-coated paper, cut to a calculated size, dropped from an airplane. A small quantity of the material will reflect as much energy as an aircraft.

X-Band. Refers to wavelengths around 3 cm.

XMTR. X-band transmitter-receiver component for airborne radar.

XT-1. Radiation Laboratory designation for SCR-584 development equipment.

Yagi Antenna. *See* antenna, yagi.

YQ. 11- and 170-cm shipborne radar beacon equipment for use with Cadillac airborne early-warning systems.

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HARP—MATERIAL WITH ARTIFICIALLY CONSTRUCTED DIELECTRIC CONSTANT AND PERMEABILITY

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NDCrc-53	Massachusetts Institute of Technology Cambridge, Massachusetts	Superseded by OEMsr-262
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OEMsr-362	Purdue Research Foundation Lafayette, Indiana	Crystal detectors
OEMsr-369	Zenith Radio Corporation Chicago, Illinois	Lightweight range-only unit
OEMsr-380	Sylvania Electric Products, Inc. (formerly Hygrade Sylvania, Inc.) Emporium, Pennsylvania	A special tunable intermediate frequency amplifier
OEMsr-382	Brown University Providence, Rhode Island	Cathode-ray tube project
OEMsr-386	Eastman Kodak Company Rochester, New York	Microwave absorbent paint
OEMsr-387	University of Pennsylvania, Trustees of the, Philadelphia, Pennsylvania	Radar-ranging system and high-frequency video amplifiers
OEMsr-388	University of Pennsylvania, Trustees of the, Philadelphia, Pennsylvania	Crystal research
OEMsr-429	Cornell University Ithaca, New York	Theoretical aid
OEMsr-443	RCA Victor Division (License Division Laboratory) Camden, New Jersey	Loran receiver for receiver trainer
OEMsr-477	RCA Victor Division Harrison, New Jersey	Tube model shop services for Columbia Radiation Laboratory
OEMsr-485	Columbia University, Trustees of, New York, New York	Columbia Radiation Laboratory

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-486	Harvey Radio Laboratories, Inc. Cambridge, Massachusetts	Six transmitting sets for long-range navigation project
OEMsr-507	Radio Engineering Laboratories, Inc. Long Island City, New York	Thirty-six Loran transmitters
OEMsr-511	Harvey-Wells Communications, Inc. Southbridge, Massachusetts	Fifteen Loran receivers
OEMsr-540	General Electric Company Schenectady, New York	Precision aircraft scanners
OEMsr-543	General Electric Company Schenectady, New York	Two truck mounted XT-1A anti-aircraft fire-control radars
OEMsr-546	University of Colorado Boulder, Colorado	Stable noncrystal controlled low frequency oscillator
OEMsr-557	General Electric Company	Four AGL-1 equipments
OEMsr-560	Kansas State College Manhattan, Kansas	Time-delay measuring instruments
OEMsr-582	General Electric Company Fort Wayne, Indiana and Pittsfield, Massachusetts	Transformer model shop
OEMsr-583	Sylvania Electric Products Emporium, Pennsylvania	Special signal generators
OEMsr-589	Raytheon Manufacturing Newton, Massachusetts	Transformer model shop
OEMsr-609	Leland Electric Company Dayton, Ohio	Three-phase aircraft alternator
OEMsr-619	American Machine Defense Corporation	Precision antenna mount for use with the CXBL set (SM Prototype)
OEMsr-633	Fada Radio & Electric Company Long Island City, New York	Loran receivers
OEMsr-634	Carnegie Institution of Washington, Geophysical Laboratory Washington, D. C.	Cathode-ray tube screens
OEMsr-642	Sperry Gyroscope Company Garden City, New York	AGL-2 fire control system
OEMsr-652	University of California Berkeley, California	High-vacuum switch
OEMsr-663	Gilfillen Bros., Inc. Los Angeles, California	Ground-control-of-approach landing systems AN/MPN-1 (XE-1) and construction of two
OEMsr-684	RCA Victor Division (RCA) Princeton, New Jersey	Lightweight Racon Development (BUPX)
OEMsr-689	Foxboro Company Foxboro, Massachusetts	Trainer for SCR-584, anti-aircraft fire-control radar
OEMsr-691	RCA Victor Division (RCA Laboratories) Camden, New Jersey	UHF Propagation Studies
OEMsr-709	Westinghouse Electric & Manufacturing Company Bloomfield, New Jersey	High-pressure spark gap
OEMsr-723	General Electric Company Schenectady, New York	Loran receivers
OEMsr-728	State College of Washington Pullman, Washington	Microwave propagation studies
OEMsr-768	Cornell University Ithaca, New York	Theoretical aid
OEMsr-770	Harvey-Wells Communications, Inc. Southbridge, Massachusetts	Fifty (50) Loran receivers
OEMsr-777	Western Electric Company (BTL)	Interference and field strength study
OEMsr-781	Rensselaer Polytechnic Institute Troy, New York	Trigger circuits

Contract Number	Name and Address of Contractor	Subject
OEMsr-789	Radio Manufacturing Engineering Laboratories, Inc. Long Island City, New York	Five (5) Loran training equipment
OEMsr-805	Harvey Radio Laboratories, Inc. Cambridge, Massachusetts	Twenty (20) Loran transmitters
OEMsr-812	Fairchild Camera & Instrument Corporation (formerly Fairchild Aviation Corporation) Jamaica, New York	(a) AGL central-station computer and (b) AGS gyro sight and spinner mount
OEMsr-821	Franklin Institute (Bartol Research Foundation) Philadelphia, Pennsylvania	Crystal clock for Loran receiver
OEMsr-832	Philco Corporation Philadelphia, Pennsylvania	LHTR unit for ARO radar and construction of six (6)
OEMsr-872	RCA Victor Division (RCA) Harrison, New Jersey	RF tube development
OEMsr-874	Fairchild Aviation Corporation Jamaica, New York	Range follow-up for ARO
OEMsr-890	Emerson Radio & Phonograph Corporation New York, New York	Trainer for SH radar
OEMsr-900	Carnegie Institute of Technology Pittsburgh, Pennsylvania	Dark-trace cathode-ray tubes
OEMsr-918	Galvin Manufacturing Corporation Chicago, Illinois	BPP, portable radar beacon (AN/PPN-2)
OEMsr-960	Dalmo-Victor, Inc. San Francisco, California	Development of radar scanners
OEMsr-972	Galvin Manufacturing Corporation Chicago, Illinois	Airborne range only ARO and airborne
OEMsr-977	RCA Victor Division (License Division Laboratory) Camden, New Jersey	Loran receiver developments
OEMsr-988	Sylvania Electric Products, Inc. Emporium, Pennsylvania	Radar tube for pulsed and CW operation
OEMsr-969	Sylvania Electric Products Salem, Massachusetts	Tube model shop
OEMsr-1022	Stevens Institute of Technology Hoboken, New Jersey	Development of electric brushes through power metallurgy
OEMsr-1025	RCA Victor Division Camden, New Jersey	Lightweight tail warning system (AN/APS-13)
OEMsr-1029	RCA Victor Division (License Division Laboratory) Camden, New Jersey	Lodar direction-finding receivers
OEMsr-1032	Kuthe Electric Company Newark, New Jersey	Development of the H-50 hydrogen thyratron
OEMsr-1043	RCA Victor Division Lancaster, Pennsylvania	Radar tube model shop
OEMsr-1044	Librascope, Incorporated Burbank, California	Radar bombing computers and ballistic computer for gun director Mark 56
OEMsr-1052	Galvin Manufacturing Corporation Chicago, Illinois	BGS beacons, construction of Forty
OEMsr-1054	Douglas Aircraft Company Santa Monica, California	Antenna installation for project Eagle (AN/APQ-7)
OEMsr-1089	International Projector Corporation New York, New York	Model of scanning antenna for Eagle (AN/APQ-7)
OEMsr-1091	Wilcox & Gibbs Sewing Machine Company New York, New York	Equation solver for SM and SCR-615 trainers
OEMsr-1112	Westinghouse Electric & Manufacturing Company Sharon, Pennsylvania	Transformer model shop I
OEMsr-1127	RCA Victor Division (National Broadcasting Company) Camden, New Jersey	Relay radar system

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1139	E. I. du Pont de Nemours, Inc. Wilmington, Delaware	Research on sintering of boron and laboratory preparation of pure germanium
OEMsr-1140	Allen B. DuMont Laboratories, Inc. Passaic, New Jersey	P3I indicator units
OEMsr-1141	Allen B. DuMont Laboratories, Inc. Passaic, New Jersey	Development of cathode-ray tube screens
OEMsr-1143	Emerson Radio & Phonograph Corporation New York, New York	Power supply for lodar receivers
OEMsr-1146	Machlett Laboratories, Inc. Springfield, Connecticut	High-power S-band magnetron
OEMsr-1149	General Electric Company Schenectady, New York	Gyro-lead computer sight for the AGS radar
OEMsr-1162	Massachusetts Institute of Technology (Servomechanisms Laboratory) Cambridge, Massachusetts	Servos for gun director Mark 56
OEMsr-1165	Westinghouse Electric & Manufacturing Company Bloomfield, New Jersey	K-band transmitter tube developments
OEMsr-1167	Chrysler Corporation Detroit, Michigan	Radar scanning units for SCR-584 and gun director Mark 56
OEMsr-1186	Sylvania Electric Products, Inc. Salem, Massachusetts	K-band RF head
OEMsr-1199	E. I. du Pont de Nemours, Inc. Wilmington, Delaware	HARP protective coatings
OEMsr-1212	Western Electric Company New York, New York	Thermistors for RF power measurement
OEMsr-1218	Western Electric Company (BTL) New York, New York	Broad-band TR and anti TR
OEMsr-1220	Franklin Institute (Bartol Research Foundation) Philadelphia, Pennsylvania	Loran supersonic trainer
OEMsr-1239	Westinghouse Electric & Manufacturing Company Sharon, Pennsylvania	Transformer model shop II
OEMsr-1242	Chicago Telephone & Supply Company Elkhart, Indiana	Special winding machine
OEMsr-1269	Utah Radio Products Company Chicago, Illinois	Design and sample production of pulse transformers
OEMsr-1283	Federal Telephone & Radio Corporation Newark, New Jersey	High impedance cable
OEMsr-1291	Maguire Industries, Inc. (General Electronics Industries Division) Greenwich, Connecticut	Stabilized scanner for the H2K radar and the construction of five (5)
OEMsr-1295	Sylvania Electric Products, Inc. Emporium, Pennsylvania	Cathode-ray tube [illegible]ens
OEMsr-1299	General Electric Company Schenectady, New York	Gun director Mark 56
OEMsr-1303	General Electric Company Schenectady, New York	Broad-band TR and anti TR
OEMsr-1311	California Institute of Technology Pasadena, California	Precision measurement of waveguide discontinuities
OEMsr-1336	General Electric Company Schenectady, New York	Stable base unit for radar antenna
OEMsr-1337	Sperry Products, Inc. Hoboken, New Jersey	MTB computing radar sight
OEMsr-1338	International Business Machines Corporation Endicott, New York	Counter for Mark III Loran indicator
OEMsr-1352	Sylvania Electric Products, Inc. Salem, Massachusetts	Transformer model shop

Contract Number	*Name and Address of Contractor*	*Subject*
OEMsr-1358	Fairchild Camera & Instrument Corporation Jamaica, New York	Cameras for aerial radar photography
OEMsr-1360	University of Michigan Ann Arbor, Michigan	Infrared absorption by water vapor
OEMsr-1361	American Type Founders Elizabeth, New Jersey	Antenna mounts for high-resolution radar
OEMsr-1377	General Electric Company Schenectady, New York	K-band crystals
OEMsr-1394	General Electric Company Schenectady, New York	Components for two (2) SCI radars (CXHR)
OEMsr-1408	Western Electric Company (BTL) New York, New York	Germanium crystal rectifiers for radar
OEMsr-1409	Western Electric Company (BTL) New York, New York	High-power enclosed fixed-gaps
Purchase Order 600,072	Western Electric Company New York, New York	Procurement of type D-160207 oscillator
Purchase Order 600,073	Western Electric Company New York, New York	Procurement of type D-160537 magnetrons
Order TPS-38541	General Electric Company Schenectady, New York	Procurement of one square-wave generator and two oscilloscopes

SERVICE PROJECT NUMBERS

The projects listed below were transmitted to the Executive Secretary, NDRC, from the War or Navy Department through either the War Department Liaison Officer for NDRC or the Office of Research and Inventions (formerly the Coordinator of Research and Development), Navy Department.

Service Project Number	*Subject*
	Army-Navy Projects
AN-2	Naloc committee project, in which several NDRC Divisions were concerned. Division 14 was concerned with Cachalot.
AN-3	Corner reflectors for life rafts to increase their range of detection by airborne microwave equipment. Extended to consultant to Navy on preproduction engineering of reflectors MX-137/A, MX-138/A, and MX-180/A and to their procurement.
AN-7	Low-altitude bombing attachment for AN/APS-1, AN/APQ-5A. Consultant.
AN-11	Mark V IFF. Part concerned with antenna mount accepted.
AN-18	Development of low frequency Loran with consultant service to the Army. Extension to establishment of a 3-station chain, testing and procurement accepted. Extension to participation of Coast Guard in tests accepted.
AN-19	Assistance to NBS on radio-frequency standards.
AN-21	Consultant service on K-band AN/APS-30 series and AN/APQ-34. Extended to radomes for AN/APS-32, 34. See AC-232.10.
AN-24	Development of ground position indicators to be used with the AN/APQ-34 and other equipments.
AN-25	K-band components and techniques.
AN-27	Airborne identification for propeller modulation.
	Navy Projects
NA-104	Lightweight X-band search equipment for aircraft.
NA-109	Stabilizing, control equipment, and target seeking device for radio controlled aircraft; BASN. Divisions 5, 14, 15.
NA-112	Relay radar, AN/APS-14.
NA-113	Radar and timing equipment for LAB, AN/APQ-5, low-altitude blind bombing, using ASV now in production.
NA-117	Development of radar trainers in connection with celestial navigation trainers and observational trainers.
NA-125	Improved AI equipment with AJ features (AIA-1).
NA-127	Stabilization of airborne radar antenna systems. Continuation accepted for test of AN/APA-15, K-band spinner, AN/APS-1 design improvement.
NA-128	Development of SM trainers.
NA-129	Trainer for the type ASH radar, advisory service.
NA-130	Lightweight radar for controlling searchlights in airplanes.
NA-131	Aircraft identification system.
NA-132	Automatic frequency control with application to airborne systems.
NA-135	Low-altitude bombing trainers for type ASG-1 radar.
NA-141	Trainer for GCA. Extended to ground-clutter simulator.
NA-142	Loran bench trainer to use with a Link celestial navigation trainer. Extended to construction of 5.
NA-160	Trainers for radar equipments AN/APQ-13 and AN/APS-15 (H2X): supersonic trainers.
NA-163	Racons to be used with X-band radar equipment.
NA-165	Universal A-J trainer.
NA-166	Use of terrain models in radar planning; Rapid.
NA-173	X-band Vixen.
NA-178	Cadillac, AEW or airborne early warning system. Extended to: Procurement of 40 airborne systems; procurement of Black Maria; consultant on GE production; Block III relay radar with construction of 40; ship-centering PPI.

Service Project Number	*Subject*
	Navy Projects (Continued)
	design and construction of 42; Cadillac 2; 11 CIC's for B-17's; Cadillac 3; assistance to Navy on large antenna and CIC indicators; extension to Block V relay radar accepted as adviser only.
NA-181	Consultant to BuAer and BuShips on development of K-band test set by Aircraft Radio Corporation.
NA-182	Application of AN/APG-5 radar equipment to lead computing sights Marks 18 and 21. Consultant on tying-in ARO with Mark 18 and camera tests.
NA-184	Development of test equipment for field maintenance of airborne radio and radar systems, with consultant services. Superseded NS-283 and NS-284. Extended to X-band kits of cables and adaptors.
NA-186	Fifteen AN/APG-13 radar operator trainers.
NA-192	GPI for APS-1. Cancelled on acceptance of AN-24.
NA-196	Study of interference fields caused by airborne radar equipment and its components.
NA-201	Mechanism for torpedo attack trainer.
NA-202	High power intercept radar, HPX.
NA-205	Modification of AN/APG-13A to Overland Falcon for Navy aircraft.
NA-207	Development of AEW trainer.
NA-209	Stub antennas for use on high speed aircraft. Referred to Divisions 13, 14, 15. Assigned to Division 15. Coordination with 13 and 14 approved.
NA-210	Consultant on detection of Schnorkel by airborne radar.
NA-222	Application of HARP material to test equipment.
NA-227	Fifty short-time-constant kits for AN/APS-2A, 2D for use against Schnorkel.
NA-228	Investigation of X- and S-band antenna patterns for guided missile applications.
NA-229	Multiple indicators for AN/APS-30-T1. Accepted as adviser service only.
NO-95	Combined radar with Sperry-Draper sight; RO for Mark 51.
NO-101	(a) Radar range finder for Ford aircraft fire control. Project taken over by Army Air Corps; (b) radar fire control for 0.50 cal. one-man turret. Plans changed from PB2Y3 to B-24 tail turret.
NO-102	Radar fire control for flights of 3 seconds, of single seat fighters. Combined with NO-101.
NO-115	Radar homing bomb—Pelican. Directive assigned to Division 5 with RL consultant for radar equipment, RHB.
NO-155	Blind firing radar for the Mark 52 director; advisor.
NO-156	Lightweight antenna for Mark 8 fire-control radar.
NO-166	Intermediate range radar and gun director, Mark 56.
	Cooperative Project with Division 7
NO-172	Maneuvering-board techniques for radar-directed torpedo attacks. Extended to advisor on procurement and installation of Torpedo Director Mark 33.
NO-182	Dynamic accuracy of synchro systems. Transferred from Division 6 to Div. 14, RL, Group 56. The section dealing with effect of capacity mismatch was accepted.
NO-184	IFF transponders for interrogation of fire-control equipment.
NO-214	Ballistic range converter, AN/APA-30, ASD-1 attachment; Mk 14 sight. Extended to procurement.
NO-225	Shore-bombardment beacons. Extended to design and model-shop production of Mark 2, Mods. 0 and 1 beacons. Extended to consultant service.
NO-277	Development of trainer for R. E. Mark 8, Mod. 3 and Mark 13, Mod. 0.
NO-295	RL, Construction of 6 Auto-Vulture, integrated with Bomb Director Mk3 and Pilot's Universal Sighting Systems.
NP-3	Course in OBJ radar training material.
NP-4	Training of personnel in installation and maintenance of SX-radar.
NR-103	Detection and ranging system analogous to radar, using pulsed infra-red radiation. Advisor service to Division 16 accepted by Division 14.
NS-100	Recognition system.
NS-101	Radar for aircraft carriers to determine the altitude of approaching bombers, CXBL, SM.
NS-107	Microwave detection equipment for destroyers; led to SG.
NS-108	Microwave detection equipment for submarine chasers; SF, SU; collaboration with Submarine Signal Company.
NS-114	Microwave radar for motor torpedo boats.
NS-118	Small, lightweight radar equipment for surface-search by motor torpedo boats; SO. Consultant. Extended to beam fanning antenna for SO-12. Advisor service only for SO-12M requested.

Service Project Number	*Subject*
	Navy Projects (Continued)
NS-119	Airborne combined Mark III-G transponder and Mark III interrogator responser; similar to SC-30; collaboration with Hazeltine.
NS-120	Tracer for superimposing PPI pattern for SG and SF; VPR.
NS-126	Ground- and airborne-radar beacons for use with X- and S-band search radar equipments; BGS, BGX. *See* NS-162.
NS-127	Antenna-stabilizing and director-correction unit (RASD).
NS-131	Remote-plan indicator (dark trace tubes).
NS-133	Consultant to the Navy on the manufacture of equipment for stabilization of shipborne-radar search-equipment.
NS-135	Preparation of material suitable for publication in the radar technical bulletins of the Navy Department.
NS-138	ASJ tail-warning radar system for aircraft; advisor.
NS-148	Broad banding techniques.
NS-149	Precision remote PPI; advisor on VF and VF-1.
NS-153	Remote PPI for SR radar. Consultant or advisor on projects of this type.
NS-156	Consulting services on SP fighter-director radar; a smaller model of SM.
NS-162	Consulting service to the Navy on Philco contract (later given to Galvin) for radar model X-YM (BGX) racon equipment. Extended to training for production testing and to theory of operation.
NS-167	Camera suitable for taking pictures of a remote PPI screen, SF, SG.
NS-169	SSV trainers for use with SF and SG search radar. Extended to consultant on electronic parts and advisor on mechanical target control for trainers for SA, SC, SK and SR series.
NS-171	Consultant to the Navy on AI, AN/APS-6.
NS-174	Consulting services to the Navy in the production of projection plan position indicators.
NS-175	Consulting service on model SG-3 and SU radar equipments. Advisor status only requested.
NS-176	Study of SCI methods, including improvements in antenna systems. See NS-194.
NS-177	Improvement of shock, vibration and blast resistance of radar equipment.
NS-178	Transponder beacon with additional frequencies for use with AN/APS-1.
NS-184	Suitable antenna for overhead search and warning. Advisor status only requested.
NS-185	Temperature compensated insulation material for use with rotary joints.
NS-186	Adaptation of Mark III interrogator-responsers and model ABK series IFF transponder equipments.
NS-188	Coded corner reflectors.
NS-190	Consultant to Navy on the production of beacon synchroscopes.
NS-192	Radar transponder beacons—automatic switching equipment.
NS-194	SCI shipborne radar to succeed SM and SP; SX. Extended to vertically scanning antenna for SP-2.
NS-196	Test equipment for transponder beacons, including consultant service on TS-120/UP.
NS-223	Advisor on interchangeable S-band units for AN/CPN-6 (BGX). Reconsideration of action on consultant service accepted.
NS-224	Advisor on repackaging SCR-598 for Marine Corps.
NS-227	Consulting service for AN/APS-[illegible] ([illegible]es).
NS-228	Consultant for AN/APS-3 (ASD[illegible])
NS-229	Consultant to the Navy for [illegible] of AN/APS-15 (H2X).
NS-232	Consultant on OBJ trainer (NS-169). Extended to supply of components of OBJ trainer.
NS-234	K-band search set for installation on PT boats; CXJG or Cindy.
NS-237	Incorporation of antijamming features in SG radar. Advisor status only requested.
NS-246	Radar test equipment (especially wave selectors and thermocouple [illegible]).
NS-249	Standards for microwave frequencies.
NS-250	High resolution X-band radar for small craft. Project Henry.
NS-265	Type and production testing of S-band radar echo-box.
NS-268	Consultant on solid dielectrics for r.f. cables. Extension to high temperature, high frequency insulation.
NS-270	Preparation of final form instruction books for Model C Loran timers.
NS-271	Preparation of final form instruction books for Model C-1 Loran timers.
NS-272	Improved circuits for Loran transmitter monitor oscilloscopes.
NS-273	Antenna coupling units for vertical Loran transmitting masts. Imbedded in NS-275.
NS-274	Elimination of screened booths at Loran transmitting stations.

Service Project Number	Subject
	Navy Projects (Continued)
NS-275	Study of Loran transmitting antennas.
NS-276	Loran test transmitter.
NS-283	Consultant on TS-12/AP, airborne X-band test set. Superseded by NA-184.
NS-284	Consultant on TS-13/AP, pulsed airborne X-band test set. Superseded by NA-184.
NS-285	Consultant on LAD pulsed S-band signal generator.
NS-286	Field engineers' test kit for S-band radar, including consultant on procurement.
NS-296	Submarine radar camouflage. Study of nonreflecting surfaces with consultation on other methods.
NS-299	Consultant on type A-121 magnetron tube.
NS-300	Plastic materials for absorption of electrical radiations. Extended to high loss insulation for wires.
NS-314	Consultant to Navy for AN/APS-1 at Philco.
NS-319	Consultant to Navy for TS-147/UP and TS-147/UP (XN).
NS-320	Consultant on AN/ART-18 and AN/ARR-17 relay links.
NS-323	Development and consultant on K-band spectrum analyzer. Extended to conversion of 10 TS-148/UP to K-band.
NS-331	Consultant on S-band and Sg-band hand-tuned echo box. Extension to Sw-band accepted.
NS-335	Crystal rectifier test set TMN-10 RL.
NS-343	Extension of Division 17 project to use of VG-type repeater with dead reckoning analyzer.
NS-351	Consultant to the Bureau of Ships for Farnsworth Television and Radio Corp. on AN/APA-5.
NS-352	Development and consultant services on S-band radar test equipment broad-banding TS-125/UP.
NS-353	Development of broad-band TR and ATR system for beacon use.
NS-358	Consulting services on coherent pulse modification.
NS-359	Development of new SO-type indicator.
NS-360	Application of IFF Mark V/UNB to AEW radar.
NS-362	Application of IFF Mark V/UNB to SX radar.
NS-363	MTI for shipboard radars, especially SP, SR.
NS-369	Modification of SCR-584 radars for MTI.
NS-374	Reduction of altitude signals in airborne radar.
NS-375	Assistance to US Navy Radio and Sound Laboratory on development of shipboard antenna systems.
NS-376	Mk V IFF feed for AN/CPS-6 antenna.
NS-378	Panoramic radar. Advisor service only accepted.
	Army Projects
AC-1	Precision bombing, Eagle. Procurement of antenna housings. Consultant for problems on antenna within leading edge of wing. Replaced by AC-232.01.
AC-35	AI-3 system for installation in the XA-26B type airplane.
AC-42	Radar system and equipment for controlling target-seeking bombs. RHB. Transferred to Division 5.
AC-44	Radar-marker float. See AN-3. Replaced by AC-263.08.
AC-51	Radar system (SRB) and auxiliary equipment for controlling target-seeking bombs. Transferred to Division 5.
AC-57	Plan for the South Atlantic Loran system.
AC-58	SS Loran system.
AC-68	Test of TG Loran.
AC-72	Camera accessories for recording blind-bombing radar display.
AC-81	Automatic range finder. See AC-235.01.
AC-90	Dielectric properties of synthetic resin glues. Replaced by AC-232.06.
AC-97	Detection of armored vehicles by means of radar. Replaced by AC-234.02.
AC-106	Procurement of 25 long range plotting boards and kits for SCR-584. Replaced by AC-233.01.
AC-107	Investigation of radar requirements on 3-phase 208/120 volt Wye, 400 cycle AC aircraft power supply.
AC-111	Nosmo: tie-in of Norden bombsight and pulse Doppler with H2X. Replaced by AC-232.08.
AC-112	Three-tone PPI. Replaced by AC-234.03.
AC-118	Procurement of X-band Black Maria, XCB.
AC-120	Identification of propeller modulation; Ella. Replaced by AC-233.02.

Service Project Number	*Subject*
	Army Projects (*Continued*)
AC-220.03	Remote control of rockets and pilotless aircraft. Advisor on AN/APW-1; development of AN/APW-3.
AC-228.05	Modification of 245 AN/APN-7 to AN/APN-21, for use in remote control of missiles.
AC-232	Radar bombing equipment. See the following subprojects.
AC-232.01	Precision bombing, AN/APQ-7. Formerly AC-1.
AC-232.02	Use of airborne radar over land. Extension to consultant to ATSC on development of AN/APQ-13 and AN/APQ-34 antennas by Boeing Aircraft Corp. Formerly SC-36.
AC-232.05	Cameras. See AC-72.
AC-232.06	Synthetic resin glues. Formerly AC-90.
AC-232.08	Nosmo. Formerly AC-111. Extension to consultant on production of AN/APA-46, 47 by Gibbs, requested. Extended to 1,500 manuals.
AC-232.09	Micro-H delay unit AN/APA-40A.
AC-232.10	Advisory service on precision bombing equipment, AN/APQ-34. Replaces Army part of AN-21.
AC-233	Radar recognition equipment. See the following subprojects.
AC-233.01	IFF for AGL, AGS and AI. Supersedes SC-119 and part of SC-77. Part referring to SC-119 accepted.
AC-233.02	AN/APX-15 radar modulation detection: test equipment (TS-348 A/AP, TS-364/APX-15), manuals. Extended to report on use of corner reflectors for aircraft identification. (Formerly AC-120.)
AC-233.03	Long-range plotting boards and modification kits for SCR-584; procurement of five. Formerly AC-106, SC-101.01.
AC-233.04	True speed of aircraft. Formerly SC-116.
AC-233.05	X-band Black Maria, XCB. Formerly AC-118.
AC-234	Radar warning equipment. See the following subprojects.
AC-234.01	Lightweight ASV. Extended to development of 30-inch cut-off low-altitude scanner for AN/APS-10. Formerly SC-46.
AC-234.02	Detection of armored vehicles by radar. Formerly AC-97.
AC-234.03	Three-tone PPI. Formerly AC-112.
AC-234.04	Microwave early warning radar, AN/CPS-1. Formerly SC-60 and its extensions. Extended to production of 6 Mark I MTI kits.
AC-234.05	Consultant on AEW.
AC-235	Radar fire-control equipment and systems. See following subprojects.
AC-235.01	Automatic and aided range finders: AN/APG-5, 13, 14, 21. Extended to modification kits to convert AN/APG-13A to B. Formerly AC-81, SC-69.
AC-235.02	AN/APG-15. Formerly SC-69.
AC-235.03	Toss bombing. Formerly SC-80.
AC-235.04	Advisor of AN/APG-3, 16. Formerly SC-103.
AC-236	Radar navigation equipment. See the following subprojects.
AC-236.01	Loran, long range navigation. Formerly SC-56.
AC-236.02	Consultant to ATSC on air transportable Loran, AN/CPN-11, 12. Formerly SC-109.
AC-236.04	Ground controlled landing system, GCA. Formerly SC-53.
AC-236.05	Air transportable GCA, AN/CPN-4. Formerly SC-72.
AC-236.06	Advisory service on automatic radar beacon ranging system with AN/APN-34 and AN/GPN-4.
AC-237	Radar test equipment. Supersedes SC-106. See the following subprojects.
AC-237.01	Consultant on TS-125/AP power meter. Formerly SC-106.01.
AC-237.04	Consultant on directional coupler APA-13. Formerly SC-106.04.
AC-237.06	K-band test equipment.
AC-238.01	Dielectric consultation and tests.
AC-238.06	Reduction of interference. See NA-196.
AC-239.01	SCR-615; height finder for GCI. Formerly SC-71.
AC-239.03	AN/CPS-4; Beavertail height-finder. Formerly SC-75.
AC-239.04	AN/TPS-10; light mountain radar. Formerly SC-107.
AC-239.05	AN/CPS-6; V-beam or "Merry-go-round." Formerly SC-74.
AC-262	Training equipment and systems. Formerly SC-62.
AC-262.01	Trainer AN/APQ-5-T1(XA). Formerly SC-62.01.
AC-262.09	Crew trainer for H2X. Formerly SC-62.09.

Service Project Number	*Subject*
	Army Projects (Continued)
AC-262.10	Trainer for AN/APQ-7. Formerly SC-62.10.
AC-262.11	Radar trainer for AN/APG-15-T1. Formerly SC-62.11.
AC-262.12	Procurement of trainers AN/APQ-13-T1. Formerly SC-62.12.
AC-262.14	Supersonic trainer, AN/APQ-T1, for precision bombing radars.
AC-263	Radar beacons. See following subprojects.
AC-263.02	AN/CPN-8, BPS. Formerly SC-63.02.
AC-263.03	AN/CPN-6, BGX. Formerly SC-63.03.
AC-263.04	AN/UPN-1, 2; BUPS. Formerly SC-63.04.
AC-263.05	AN/UPN-3, 4; AN/APN-11; BUPX. Formerly SC-63.05.
AC-263.06	K-band beacons. Formerly SC-63.06.
AC-263.07	Development of S-band beacon, AN/APN-19; Rosebud.
AC-263.08	Radar marker float. Formerly AC-44.
AC-301	General directive for MTI. See the following for specific request. Acceptance recommended July 30, 1945.
AC-301.01	Consultant on development of MTI Mk II for AN/CPS-1.
OD-47	Radio range-finder for aircraft.
OD-54	Information for the preparation of bombing tables.
OD-94	Combined director and radar position-finder for automatic weapons. Project handled by a committee of Sections D-1, D-2.
OD-175	Photographic recorder.
OD-178	Development of field chronograph T-5.
SC-6	Use of microwaves for detection purposes. General Radiation Laboratory directive. AI and ASV completed. SC-6 was broken down into a decimal system and later other numbers were assigned. See SC-51 through SC-62.
SC-6.12	Development of pulsed glide path, X-band aircraft landing system.
SC-30	Development of Mark 3-G transponder and Mark 4 interrogator-responder.
SC-32	Power supply requirements as a function of future radar circuit development.
SC-33	Weight of radar systems vs. power supply frequency.
SC-34	Survey of commutation of direct-current machinery at high altitudes. See AC-238.03.
SC-35	Use of ground radar against ground units. Now under SC-73.
SC-36	Use of airborne radar over land (NAB, H2X). Extension to Micro-H, Mark II. See AC-232.62.
SC-37	Development of radar equipment for use against motor torpedo boats. Consultant service on SCR-598, AN/FPG-1. Consultant service on AN/FPG-2.
SC-39	Improvements in IFF Mark IV.
SC-45	Antenna system for long-range ASV (LRASV).
SC-46	Antenna system for use with S-band lightweight ASV. Now X-band LWASV. Extension to include consultant on procurement. See AC-234.01. Extension to cut-off low-altitude thirty-inch scanner.
SC-50	Lightweight responder beacon equipment to work with Rebecca, AN/APB-1, or similar equipment. Superseded by SC-63.
SC-51	Aircraft interception system AI-3.
SC-52	Aircraft gun laying X-band automatic tracking set, AGL-2; advisor.
SC-53	Instrument landing; ground control of landing system, GCA. Consultant to Army and advisor on production at Gilfillan. Extended to advisor on production at FT & R. See AC-236.04.
SC-54	Microwave racons. Superseded by SC-63.
SC-55	Detection set, range only RO-1.
SC-56	Long range navigation by means of pulse transmission, Loran. Consultant on construction of Loran receivers, AN/APN-9, at RCA cancelled. Extended to procurement of TG Loran. Not extended to direct reading indicator receiver. For extension to LF Loran see AN-18. *See* AC-236.01.
SC-57	Airborne range-only radar equipment, ARO; Consultant on AN/APG-14. Procurement of 120 Units of AN/APG-13. *See* AC-235.01.
SC-58	Tail warning equipment for bombers, TWS-1, TWS-2.
SC-59	Tail warning equipment for fighter aircraft, FTW.
SC-60	Microwave early warning set, MEW and construction of 5; consultant on 21.04 to -8 procurement. Construction of one additional unit; construction of three more units with other items. Extended to beacon modification kits for AN/CPS-1A. See AC-234.04.

Service Project Number	*Subject*
	Army Projects (Continued)
SC-61	Fire control for cannon in XA-26B. See AC-35.
SC-62	Trainers for radar equipments.
SC-62.01	Consultant for trainer for AN/APQ-5 (RC-217), LAB. Number changed to AC-262.01.
SC-62.02	Consultant for bench trainer SCR-520 (RC-225).
SC-62.03	Consultant for beacon simulator for RC-225-T-1.
SC-62.04	Consultant for Link trainer for SCR-520/720.
SC-62.05	Consultant for trainer for SCR-617.
SC-62.06	Consultant for trainer for SCR-519-T3.
SC-62.07	Consultant for crew trainer for SCR-702. Amended to cover a universal AGL Trainer for AN/APG-1, 3, 8, 15 and 16.
SC-62.08	Consultant for optical projection trainer.
SC-62.09	Trainer for H2X, interim model and supersonic type. Extension to procurement. Number changed to AC-262.09.
SC-62.10	Eagle trainer AN/APQ-7-T1 with procurement of 8. Extended to procurement of 50. Number changed to AC-262.10.
SC-62.11	Development of trainer AN/APG-15-T1. Procurement of 30. Number changed to AC-262.11.
SC-62.12	Procurement of Falcon trainers. Number changed to AC-262.12.
SC-63	Racons; this directive incorporates previously accepted projects SC-50 and SC-54. For subdivision see SC-63.01-63.05.
SC-63.01	AN/CPN-3, AN/CPN-5 (BGS).
SC-63.02	AN/CPN-8 (BPS). See AC-263.02.
SC-63.03	AN/CPN-6 (BGX). See AC-263.03.
SC-63.04	AN/UPN-1, 2, formerly AN/FPN4, AN/PPN-5 (BUPS). Includes consultant service on procurement. See AC-263.04.
SC-63.05	AN/UPN-3, 4, formerly AN/PPN-6, AN/PPN-7 (BUPX). Extension includes consultant service on procurement. See AC-263.05.
SC-63.06	Development of K-band beacons. See AC-263.06.
SC-66	Proposed interim blind bombing equipments against land targets, based on SCR-717T3 components. Withheld until commitments on ASG were completed, then accepted.
SC-68	X-band attachment for long range ASV.
SC-69	Airborne gun sight; AGS. Consultant services on AN/APG-15. See AC-235.02.
SC-71	SCR-615. Height finder for GCI. See AC-239.01.
SC-72	Consultant service on air transportable ground controlled approach equipment, AN/CPN-4. See AC-236.05.
SC-73	Methods for elimination of ground clutter. Extended to procurement of 2 MTI kits for SCR-584 and consultant on MC-642. Extended to improved search-type antenna.
SC-74	Development of the V-beam GCI equipment. Extended to procurement. Extended to consultant on AN/CPS-6A. Extended to procurement of six beacon modification kits. See AC-239.05.
SC-75	"Beavertail" height finder to use with LREW and consultant to Army on its manufacture, AN/CPS-4. See AC-239.03.
SC-76	S-band Oboe equipment "Aspen," with consultant and procurement service.
SC-77	Improvement in Mark III, IFF. Extended to modification of SCR-695, SCR-729. IFF for ground radar kept; for airborne see AC-233.01.
SC-80	Radar range finder for toss bombing. Advisor. See AC-235.03.
SC-82	Advisor on dark-trace console.
SC-89	Advisor on radar for T-38 Director.
SC-94.23	Development of CW magnetron for Division 15.
SC-101	Development work and consultant service on SCR-584. (Formerly carried under SC-6.) Extended to procurement of N^3 gate and X-band kit; extended to procurement of 8 MTI kits, MC-642.
SC-101.01	Consultant service on plotting table equipment, RC-294. See AC-233.03.
SC-101.02	Consultant service on search antenna for SCR-584.
SC-101.03	Consultant service on sector scans for SCR-584; MC-645.
SC-102	Consultant on SCR-702A, B, AN/APG-1, 2. (Formerly carried under SC-6.)
SC-103	Advisor service for AN/APG-3, 16. See AC-235.04.
C-104	Dielectric consultation and tests.
SC-106	Test equipment. Subdivided into 106.01-106.05.

Service Project Number	*Subject*

Army Projects (Continued)

SC-106.01	Consultant on TS-125/AP power meter. See AC-237.01.
SC-106.02	Consultant on RF-3A/AP phantom target.
SC-106.03	Consultant on AS-15/AP antenna.
SC-106.04	Consultant on production of directional transmission line coupler for AN/APQ-13. Extension to AN/APS-15 accepted. See AC-237.04.
SC-106.05	Consultant on test equipment TS-155/UP.
SC-106.06	K-band test equipment, TS-253 (dummy load), TS-254 (power meter); extended to TS-259 (XA-) /AP. Formerly TTK-IRL.
SC-107	AN/TPS-10 "Little Abner." Extended to procurement. See AC-239.04.
SC-109	Air-transportable Loran. Extended to procurement. Extended to advisor on production at Bendix. See AC-236.02.
SC-115	Reduced titanium compounds for use as resistors.
SC-119	IFF for AGL, AGS and AI. See AC-233.01.
SC-143	Radar for automatic weapons. Not accepted, except for advisor service if needed.
SC-144	Radar mortar locator. Not accepted, except for advisor service if needed.
SC-145	Forward combat area detector. Not accepted, except for advisor service if needed.
SC-146	Field artillery radar, 2 kits for SCR-584 modification.
SC-148	High dielectric ceramics, low temperature-coefficient ceramics, piezoelectric crystals.

Advisory and Consultant Services by the Radiation Laboratory

These are in addition to the ones previously listed under AN-3, -7, -21; NA-109, -129, -181, -182, -184; NO-11[illegible], -[illegible]55, -172; NR-103; NS-101, -108, -118, -119, -133, -149, -153, -156, -162, -169, -171, -174, -175, -190, -196, -223, -224, -22[illegible], -[illegible]28, -229, -232, -265, -268, -272, -285, -286, -296, -299, -314, -319, -331, -351, -357; AC-1; SC-37, -46, -53, -56, -57, -60, -62, -6[illegible], -63.05, -72, -75, -76, -80, -82, -89, -101, -102, -103, -106.

AIA	Advisor to the Navy on production of AIA equipment.
AN/APN-4	Advisor to the Army on production of AN/APN-4 by Philco.
AN/APN-6 (BAS) AN/CPN-8 (BPS)	Consulting service to the Army on Galvin beacon production.
AN/APQ-13	Advisor to the Army for AN/APQ-13; H2X (WE).
AN/APS-1	Consultant to the Army on development of AN/APS-1.
AN/APS-3A	Advisor to the Navy for production at Sperry of AN/APS-3A.
AN/APS-6	Advisor for construction of AN/APS-6.
AN/APS-19	Advisor to the Navy on AN/APS-19.
AN/ARR-17, ART-18	Advisor to Navy on AN/ARR-17, ART-18 at Philco.
AN/MPN-1	Advisor to the Navy on all developments in connection with the "talk-down" radio equipment AN/MPN-1.
AN/PPN-3	Advisor to the Navy on production by Airadio.
AN/TPS-1B	Advisor to Bureau of Ships on MTI application.
ARO	Advisor on lightweight ARO, at Philco.
ARO	Advisor on FM ARO, at Raytheon.
ASD Equipment	Advisor to the Navy on ASD production at Sperry.
ASG, ASD, AIA Trainers	Consultant to the Navy on the development of ASG, ASD and AIA trainers.
Block V	Advisor to Bureau of Aeronautics on Block V Relay Radar Transmitter.
Bomb Director	Advisor to Bureau of Ordnance on Bomb Director MK2 Mod 0, formerly Mark 22.
DG Synchro Unit	Advisor to the Navy on "DG" Synchro Unit.
Echo Box	Advisor to Navy on WE production of X-band echo box.
Echo Box	Advisor on TS-218/UP, TS-219/UP.
FM Radar	Advisor to the Navy on the RCA contract for the development of components and systems using the FM principle.
Loran	Advisor to Navy on production of equipments.
Mark 1 and Mark 11	Advisor to the Navy on target designation transmitter Mark 11 and gun director control unit Mark 1.
Mark 19	Advisor to the Navy on the use of radar equipment Mark 19 with gun director Mark 49. Division 7 has the responsibility for the redesign of gun director Mark 49.

Service Project Number	*Subject*
	Advisory and Consultant Services by the Radiation Laboratory (*Continued*)
Photography	Advisor to the Navy on radar scope photography.
Radar Beacons	Mk 2, Mods 0 and 1. Consultant service to the Navy.
Relay Radar	Advisor for ground relay radar for Marine Corps.
SCR-615B	Consultant to the Army on production of SCR-615B. Extension of SC-71.
SG	Advisor to the Navy on SG.
SG-3	Advisor to the Navy on SG-3.
SN	Advisor to the Navy on SN.
SO-11 Antenna	Advisor to the Navy on SO-11 Antenna
SO-12	Advisor to the Navy on MTI for SO-12.
SO-12M	Advisor to the Navy on SO-12M.
SQ	Consultant to the Navy on the construction of the indicators of SQ; advisor on other components of SQ.
SRB	Advisor to the Navy on BTL development of SRB.
SU	Advisor to the Navy on SU.
TS-148/UP	Advisor to Navy on these test sets built by WEM Co.
VF	Consultant to the Navy on Raytheon production of VF (formerly P31).
YK Racons	Advisor to the Navy on the development of the model YK series of racon equipment by Philco. Consultant on production of TS-155/UP. Liaison on application of beacon development under SC-63 to glide and power driven bombs accepted.

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